PB89-194229

Estimating Air Toxics Emission from Coal and Oil Combustion Sources

Radian Corp., Research Triangle Park, NC

Prepared for:

Environmental Protection Agency, Research Triangle Park, NC

Apr 89

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-450/2-89-001	2.	3. RECIPIENT'S ACCESSION NO. PB89 194229/AS
4. TITLE AND SUBTITLE Estimating Air Toxic Emissions From Coal And Oil Combustion Sources		5. REPORT DATE April 1989
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Gary Brooks		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Radian Corporation 3200 Progress Center P.O. Box 13000 Research Triangle Park, NC 27711		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. 68-02-4392
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental PRotection Agency OAR, OAQPS, AQMD, PCS (MD-15) Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

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16. ABSTRACT

To assist groups interested in inventorying air emissions of potentially toxic substances, EPA is preparing a series of documents that compiles available information on sources and emissions of toxic substances. This document deals specifically with methods to estimate air toxic emissions from coal and oil combustion sources. Its intended audience includes Federal, State and local air pollution personnel and others interested in making estimates of toxic air pollutants emitted from coal and oil combustion sources.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Coal and Oil Combustion Estimating Air Emissions Air Toxic Substances		

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 448
	20. SECURITY CLASS *(This page)* Unclassifed	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

PB89-194229

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL INFORMATION SERVICE
SPRINGFIELD, VA. 22161

EPA-450/2-89-001
April 1989

ESTIMATING AIR TOXIC EMISSIONS FROM COAL AND OIL COMBUSTION SOURCES

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Office Of Air Quality Planning And Standards
Research Triangle Park, North Carolina 27711

April 1989

This report has been reviewed by the Office Of Air Quality Planning And Standards, U. S. Environmental Protection Agency, and approved for publication. Any mention of trade names or commercial products is not intended to constitute endorsement or recommendation for use.

EPA-450/2-89-001

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SECTION 1
PURPOSE OF DOCUMENT

The Environmental Protection Agency, State, and local air pollution control agencies are becoming increasingly aware of the presence of substances in the ambient air that may be toxic at certain concentrations. This awareness, in turn, has led to attempts to identify source/receptor relationships for these substances and to develop control programs to regulate emissions. Unfortunately, very little information is available on the ambient air concentrations of these substances or on the sources that may be discharging them to the atmosphere.

To assist groups interested in inventorying air emissions of various potentially toxic substances, EPA is preparing a series of documents such as this that compiles available information on sources and emissions of these substances. Other documents in the series are listed below:

Substance	EPA Publication Number
Acrylonitrile	EPA-450/4-84-007a
Carbon Tetrachloride	EPA-450/4-84-007b
Chloroform	EPA-450/4-84-007c
Ethylene Dichloride	EPA-450/4-84-007d
Formaldehyde	EPA-450/4-84-007e
Nickel	EPA-450/4-84-007f
Chromium	EPA-450/4-84-007g
Manganese	EPA-450/4-84-007h
Phosgene	EPA-450/4-84-007i
Epichlorohydrin	EPA-450/4-84-007j
Vinylidene Chloride	EPA-450/4-84-007k
Ethylene Oxide	EPA-450/4-84-007l
Chlorobenzenes	EPA-450/4-84-007m
Polychlorinated Biphenyls (PCBs)	EPA-450/4-84-007n
Polycyclic Organic Matter (POM)	EPA-450/4-84-007p
Benzene	EPA-450/4-84-007q

This document deals specifically with toxic air emissions from coal and oil combustion. Its intended audience includes Federal, State, and local air pollution personnel and others who are interested in locating potential combustion source emitters of these pollutants and making gross estimates of air emissions therefrom.

Because of the relatively limited amounts of data available on toxic air pollutants from coal and oil combustion, and since the configurations of many sources will not be the same as those described herein, this document is best used as a primer to inform air pollution personnel about (1) the types of pollutants found in coal and oil, (2) the formation and behavior of toxic pollutants during the combustion process, (3) factors affecting the release of toxics from combustion sources, and (4) available emissions information indicating the potential for toxic air pollutants to be released into the air from coal and oil combustion.

The reader is strongly cautioned against using the emissions information contained in this document to try to develop an exact assessment of emissions from any particular facility. Since insufficient data are available to develop statistical estimates of the accuracy of these emission factors, no estimate can be made of the error that could result when these factors are used to calculate emissions from any given facility. It is possible, in some extreme cases, that orders-of-magnitude differences could result between actual and calculated emissions, depending on differences in source configurations, control equipment, and operating practices. Thus, in situations where an accurate assessment of combustion source toxic emissions is necessary, source-specific information should be obtained to confirm the existence of particular emitting operations, the types and effectiveness of control measures, and the impact of operating practices. A source test and/or material balance should be considered as the best means to determine air emissions directly from an operation.

SECTION 2
OVERVIEW OF DOCUMENT CONTENTS

As noted in Section 1, the purpose of this document is to assist Federal, State, and local air pollution agencies and others who are interested in locating potential combustion source toxic air pollutant emitters and making gross estimates of air emissions therefrom. Because of the relatively limited data available on toxics from all types of coal and oil combustion sources, the information summarized in this document does not and should not be assumed to represent the source configuration or emissions associated with any particular facility.

The principal basis for the information presented in this document is a recent final, but unpublished EPA, report on coal and oil combustion source toxic emissions. The report reference is given below:

> Mead, R. C.; Post, B. K.; Brooks, G. W.
> Summary of Trace Emissions From and Recommendations of Risk Assessment Methodologies for Coal and Oil Combustion Sources. Prepared under EPA Contract No. 68-02-3889. Radian Corporation, Research Triangle Park, North Carolina. July 1986.

The 1986 report was prepared from data gathered through extensive computerized literature searching (see Appendix A) and telephone/letter contacts with over 50 individuals affiliated with organizations that address toxic air emissions from combustion sources. Examples of the groups contacted include the U. S. EPA (several offices), the U. S. Department of Energy (DOE), utility industry associations such as the Electric Power Research Institute (EPRI) and the Utility Air Regulatory Group (UARG), the Council of Industrial Boiler Owners (CIBO), the American Boiler Manufacturers Association (ABMA), and the American Petroleum Institute (API).

This section provides an overview of the contents of this document. It briefly outlines the nature, extent, and format of the material presented in the remaining sections of this report.

Section 3 of this document provides a brief summary of the gross consumption of coal and oil in the United States, provides quantitative dates on the levels of selected toxics in fuels, and describes the various mechanisms that affect the release of toxic pollutants during coal and oil combustion.

Section 4 contains emission factors for arsenic, beryllium, cadmium, chromium, copper, lead, manganese, mercury, nickel, radionuclides, formaldehyde, and POM emissions from coal and oil combustion sources. Emission factors are organized in the following hierarchy:

- Fuel type
  - Pollutant
    - Combustion sector
      - Boiler type

Controlled and uncontrolled factors are presented for all pollutants. For trace metals, the data are presented in terms of measured factors (based on source tests) and calculated factors (based on levels of trace metals in the fuels and theoretical partitioning assumptions). In addition to the emission factors, control device effectiveness percentages (i.e., percent removal levels) are provided for the trace metals based on source test results.

Section 5 of this document summarizes available procedures for source sampling and analysis of coal and oil combustion toxic emissions. The discussion is focused on the 12 selected coal and oil combustion toxics studied in this document. Details are not prescribed nor is any EPA endorsement given to or implied for any of these sampling and analysis procedures. This document provides an overview of applicable sampling procedures, citing references for those interested in conducting source tests.

Section 6 contains a bibliography of all references cited in the document, including appendices.

The document also contains three appendices. Appendix A contains a description of how the data base of trace element content values (Section 3) and toxic pollutant emission factors (Section 4) was developed. Fuel heating values for typical coals and oils are presented in Appendix B. These heating values are used in conjunction with trace element content data to calculate emission factors. Appendix C contains all individual data values used to generate the summarized emission factor averages and ranges presented in Section 4. Only measured emission factor data are given in Appendix C.

This document does not contain any discussion of health or other environmental effects of coal and oil combustion toxic emissions, nor does it include any discussion of ambient air levels.

Comments on the contents or usefulness of this document are welcomed, as is any information on process descriptions, operating practices, control measures, and emissions information that would enable EPA to improve its contents. All comments should be sent to:

Chief, Pollutant Characterization Section (MD-15)
Noncriteria Pollutant Programs Branch
U. S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

SECTION 3

BACKGROUND

In this section of the document, information is provided on: (1) the various types of coals and oils consumed in the United States; (2) the quantities of coal and oil burned by utility, industrial, commercial/institutional, and residential sectors; (3) typical toxic pollutant concentrations in coal and oil; (4) the formation and behavior of toxic pollutants during combustion; and (5) the effects of combustion source design and control technology on toxic emissions from coal and oil combustion.

FUEL CONSUMPTION

The amount and type of fuel consumed by combustion sources has a direct bearing on trace element emissions. This section characterizes U. S. consumption of coal and oil.

Types of Coal and Oil

Coal can be divided into three major types - bituminous, lignite, and anthracite. Subbituminous coal is sometimes separated out from bituminous coal as another major type. On a fuel consumption basis, about 95 percent of all coal combusted in the U. S. is bituminous, 4 percent is lignite, and 1 percent is anthracite (Baig et al., 1981). Figure 3-1 shows the major coal fields in the U. S. and the type of coal mined in each. The heating value and trace element content of coal varies by coal type and geographic region. Appendix B details typical heating values by coal type and geographic source of the coal.

Two major categories of fuel oil are burned by combustion sources - residual and distillate oils. These oils are further distinguished by grade numbers, with numbers 1 and 2 being distillate oils, numbers 5 and 6

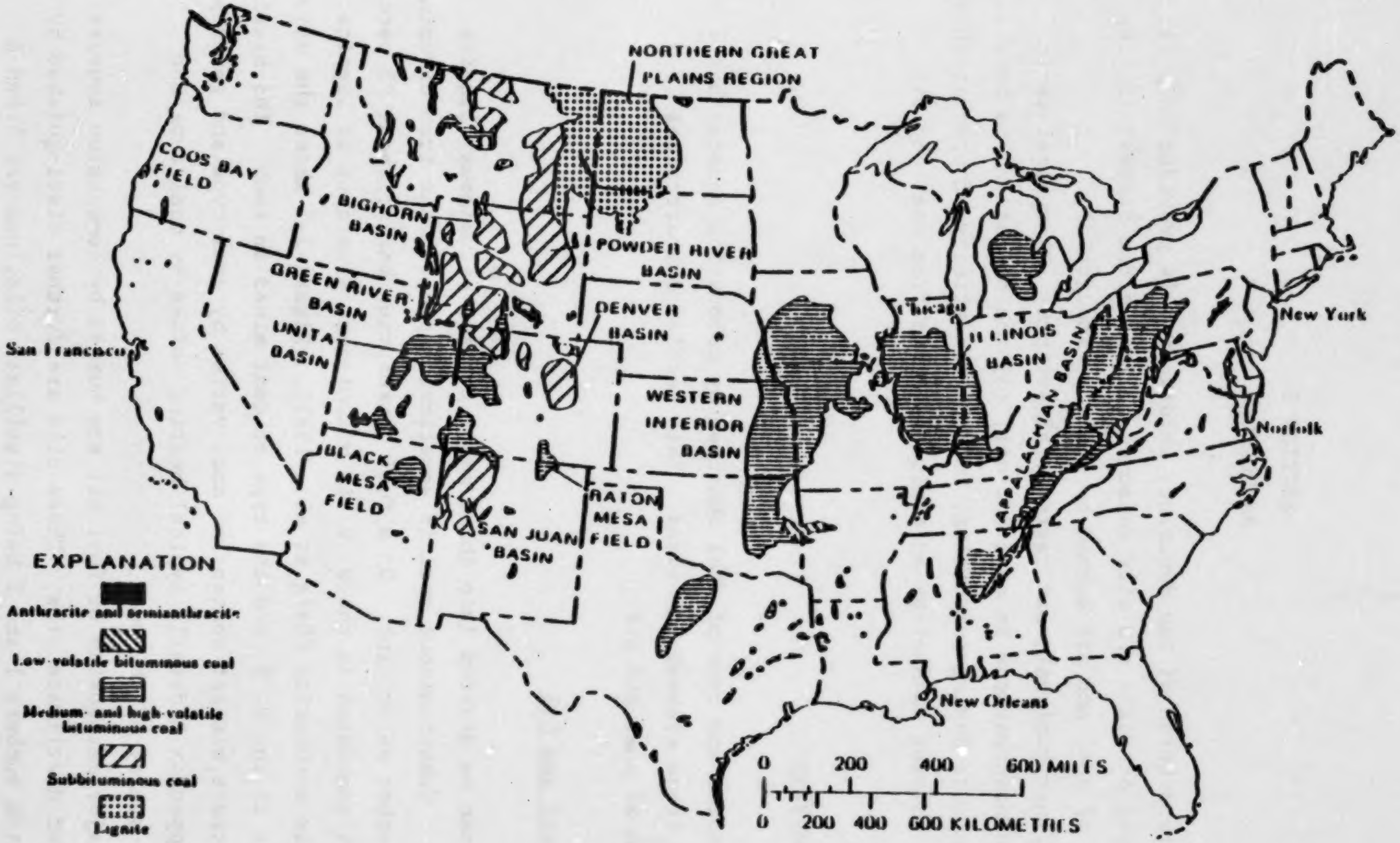
NORTHERN GREAT PLAINS REGION
COOS BAY FIELD
BIGHORN BASIN
POWDER RIVER BASIN
GREEN RIVER BASIN
DENVER BASIN
UNITA BASIN
WESTERN INTERIOR BASIN
BLACK MESA FIELD
RATON MESA FIELD
SAN JUAN BASIN
ILLINOIS BASIN
APPALACHIAN BASIN
Chicago
New York
Norfolk
New Orleans
San Francisco
EXPLANATION
Anthracite and semianthracite
Low-volatile bituminous coal
Medium- and high-volatile bituminous coal
Subbituminous coal
Lignite
0 200 400 600 MILES
0 200 400 600 KILOMETRES

Figure 3-1. Coal fields in the United States (excluding Alaska)

Source: Braunstein et al., 1977

residual, and number 4 either distillate or a mixture of distillate and residual oils. Typical heating values for fuel oils are presented in Appendix B on the basis of the geographic section of the country in which they are consumed.

Fuel Use by Combustion Sector

Table 3-1 summarizes Department of Energy data on 1986 U. S. coal and oil use by combustion sector (Energy Information Agency, 1987). In 1986, a total of almost 22,600 x 10^{12} Btu of coal and oil were consumed by the utility, industrial, commercial/institutional, and residential sectors. As shown in Table 3-1, the utility sector consumed the most fuel (over 15,800 x 10^{12} Btu). About 91 percent of this fuel consumption (by heat content) was coal, about 8.6 percent was residual oil, and less than one percent was distillate oil. Bituminous and lignite coal consumption was far greater than anthracite coal consumption. Pennsylvania is the only State where utilities consume anthracite coal. Proportions of coal versus oil consumed varied greatly from State to State, with utilities in some States (California, Oregon, Hawaii, Idaho, and Rhode Island) consuming no coal, while utilities in other States (Alabama, Arkansas, Iowa, Ohio, South Dakota, Utah, Washington, and others) consume very little oil and rely almost exclusively on coal (Energy Information Agency, 1987).

The industrial sector consumed about 4,700 x 10^{12} Btu of coal and oil in 1986, of which about 57 percent was coal, 18 percent was residual oil and 25 percent was distillate oil. As in the utility sector, some States relied more heavily on coal while others relied more heavily on oil (Energy Information Agency, 1987).

In the commercial sector, total coal and oil consumption was about 950 x 10^{12} Btu, with bituminous and lignite coals accounting for 10 percent, anthracite for 1.3 percent, residual oil for 26 percent, and distillate oil for 63 percent of this total. Pennsylvania, Ohio, and Indiana consumed large amounts of coal relative to oil; and Pennsylvania also accounted for most of the anthracite coal consumption (Energy Information Agency, 1987).

TABLE 3-1. U.S. FUEL CONSUMPTION BY SECTOR, 1986[a]

Sector	Coal Consumption (10^{12} Btu)			Oil Consumption (10^{12} Btu)			Total Coal and Oil Consumption
	Bituminous and Lignite	Anthracite	Total Coal	Residual	Distillate[b]	Sum of Residual and Distillate	
Utility	14,405.5	12.9	14,418.4	1,359.0	83.4	1,442.4	15,860.8
Industrial	2,638.7	11.5	2,650.2	831.4	1,200.6	2,032.0	4,682.2
Commercial/ Institutional	94.9	12.0	106.9	248.2	595.6	843.8	950.7
Residential	51.1	18.1	69.2	0.0	1,012.0	1,012.0	1,081.2
Total For All Sectors	17,190.2	54.5	17,244.7	2,438.6	2,891.6	5,330.2	22,574.9

[a] Source: Energy Information Administration, 1987

[b] For the utility sector this value includes distillate oil (#2), kerosene, and jet fuel. For the other three sectors it includes distillate oil only.

The residential sector consumed about 69.2 x 10^{12} Btu of coal and 1,012 x 10^{12} Btu of distillate oil in 1986. Residual oil is not used in residential furnaces. Pennsylvania, Ohio, New York, Indiana, and Kentucky accounted for 55 percent of national residential coal consumption. Pennsylvania used two and a half times as much anthracite as bituminous coal. New York consumed roughly equal amounts of bituminous and anthracite coal. For the other States, bituminous coal predominated.

CONCENTRATION OF SELECTED TOXIC POLLUTANTS IN FUELS

This section summarizes the available data on the toxic pollutant content of coal and oil. The discussion is focused primarily on trace metals. Information on the content of toxic organics in coal and oil was not generally available. Most of the toxic organics from combustion processes are formed during the combustion process itself. Where possible, the data are summarized by fuel type and by geographic region. Ranges, means, and standard deviations for trace element concentrations found in previous studies are presented. Typical values for the levels of each element in coals and oils are also presented.

The most comprehensive source of information on coal composition is the USGS National Coal Resources Data System (NCRDS). Geochemical and trace element data are stored within the USCHEM file of NCRDS. As of October 1982, the file contained information on 7,533 coal samples representing all U. S. coal provinces. Trace element analysis for about 4,400 coal samples were included in the data base (White et al., 1984). This computerized data system was not accessed during the current study due to time and budgetary constraints; however, a summary of the data presented in White et al. (1984) was reviewed. Pennsylvania State University also maintains a computerized data base including trace element content of coal samples. Information from this data base was published by Spackman (1982a; 1982b).

The most extensive source of published trace element data was produced by Swanson et al. of the USGS (1976). This report contains data for 799 coal samples taken from 150 producing mines and includes the most important

U. S. coal seams. Data from the Swanson study was the initial input into the USCHEM file of NCRDS.

Another significant source of published data on trace metals in coal is a study by Ruch et al. of the Illinois State Geological Survey (1974). This report contains trace element data for 82 coal samples from the Illinois basin and 19 samples from other states. Other data reviewed generally collaborate the findings reported in White et al. (1984), Swanson et al. (1976) and Ruch et al. (1974).

The trace element content of oil is not as well characterized as the trace element content of coal. Since the major sources of oil composition data vary from element to element, major references are identified in the sections on each element.

Arsenic in Fuels

Arsenic in Coal-

Data on the ranges, means, and standard deviations of arsenic in bituminous, subbituminous, anthracite, and lignite coals are presented in Tables 3-2 and 3-3. The concentration of arsenic in coal is highly variable. From the ranges presented in Table 3-3 it can be seen that arsenic concentration in individual coal samples varies over four orders of magnitude. The large standard deviations, which exceed the mean arsenic concentrations for each type of coal shown in Table 3-2, are another indication of the great variability of the data. Despite this variability, the table indicates that the average arsenic content of bituminous and lignite coals is higher than the average arsenic content of subbituminous and anthracite coals. Since the NCRDS data base, the source of the values in Table 3-2, is the most comprehensive data base currently available, it is recommended that the arithmetic means shown in the table be used as "typical" values for the arsenic content of the four types of coal.

Table 3-4 shows the arsenic content of coal by geographic region. Again, variability within each region is high, and the standard deviations approach or exceed the means. One noteworthy trend is that the average concentration of arsenic is greater in Appalachian and Interior coals than

TABLE 3-2. CONCENTRATION OF ARSENIC IN COAL BY COAL TYPE[a]

Coal Type	Number of Samples	Arsenic Concentration (ppm) Mean	Arsenic Concentration (ppm) Standard Deviation
Bituminous	3527	20.3	41.8
Subbituminous	640	6.17	15.5
Anthracite	52	7.67	19.6
Lignite	183	22.8	138

[a] Data presented in White et al., (1984); based on data in the USGS National Coal Resources Data System (NCRDS) as of 1982. Arithmetic means from this study may be used as typical values for arsenic content of these types of coals.

TABLE 3-3. RANGES OF ARSENIC CONCENTRATION IN COALS BY COAL TYPE

Coal Type	Arsenic Concentration Range (ppm)[a]
Bituminous	0.02-357
Subbituminous	0.1-16
Anthracite	NA[b]
Lignite	0.1-45

[a] Lowest and highest values reported in any of the literature reviewed. Note: The White et al., (1984) study does not list the range of values in the NCRDS. The Swanson et al., (1976) study, which is a subset of the NCRDS describing about 800 coal samples does include ranges for bituminous, subbituminous, and lignite coals from certain geographic regions.

[b] NA = not available.

TABLE 3-4. ARSENIC CONCENTRATION IN COAL BY REGION

Region	Number of Samples	Arsenic Concentration (ppm) Range	Arithmetic Mean	Standard Deviation	Reference
Appalachian	2749	---	22.2[a]	45.5	White et al., 1984; NCRDS[b]
	331	0.5-357	27	---	Swanson et al., 1976[c]
Interior	592	---	16.3[a]	23.0	White et al., 1984; NCRDS
	155	<1-240	21	---	Swanson et al., 1976
Illinois Basin[d]	82	1.7-93	14.9	18.9	Ruch et al., 1974
Gulf Province	38	---	4.74[a]	3.53	White et al., 1984; NCRDS
	34	1-16	6	---	Swanson et al., 1976
Northern Plains	371	---	6.33[a]	15.8	White et al., 1984; NCRDS
	490	<1-45	4	---	Hatch and Swanson, 1977
Rocky Mountains	512	---	4.72[a]	12.3	White et al., 1984; NCRDS
	124	<1-50	2	---	Swanson et al., 1976
Alaska	107	---	5.25[a]	4.45	White et al., 1984; NCRDS
	18	1-5	3	---	Swanson et al., 1976

---

[a] Values are based on the most comprehensive data set currently available and may be used as typical values for arsenic in coal from these regions.

[b] NCRDS = National Coal Resource Data System maintained by USGS.

[c] Data from the Swanson et al., (1976) study are included in the NCRDS. Arithmetic means from the entire NCRDS are more representative than means from Swanson, since the NCRDS contains many more coal samples. The Swanson data are included here to give an idea of the range of values for arsenic content in individual coal samples for each region.

[d] This is the Eastern portion of the Interior Province.

in other coals. This behavior is also noted with other chalcophiles such as cadmium and nickel (White et al. 1984). The arithmetic mean concentrations from the White et al. (1984) analysis of the NCRDS may be viewed as representative values for coals from each geographic region.

Arsenic in Oil-

The arsenic content of oil also varies with type of oil and with the State or country of origin. The arsenic content of crude oils varies over three orders of magnitude. The variability within residual and distillate oils appears to be somewhat less (see Tables 3-5 and 3-6). However, previous studies have produced a wide range of estimates for mean or typical arsenic concentrations in residual oils, with estimates ranging from 0.055 to 0.8 ppm. In general, the average arsenic content of crude and residual oils is greater than that of distillate oils. Table 3-6 characterizes the data reviewed in the current study in terms of the ranges of arsenic concentrations reported in oils and suggested typical values. The typical arsenic concentration of residual oil is 0.36 ppm and that of distillate oil is 0.085 ppm. These values were derived by averaging the mean or typical values reported in the most comprehensive and highest quality studies reviewed.

While the arsenic content of crude oils varies with country of origin and with State of origin within the U. S. (Anderson, 1973; PEDCO, 1982; Cato et al., 1976), the data reviewed show no clear pattern as to whether domestic or foreign oil has a higher average arsenic content (see Table 3-7).

Beryllium in Fuels

Beryllium in Coal-

The concentration of beryllium in coal varies by coal type and region in which the coal is found. As shown in Table 3-8, bituminous and lignite coals have a higher mean beryllium concentration than subbituminous and anthracite coals. In the case of subbituminous and lignite coals, the standard deviation exceeds the mean for beryllium concentration, indicating great variability in

TABLE 3-5. CONCENTRATIONS OF ARSENIC IN OIL REPORTED IN PREVIOUS STUDIES

Type of Oil	Number of Samples	Arsenic Concentration (ppm)			Reference
		Range	Mean	Standard Deviation	
Residual #6	11	<0.15-1.0	0.51	---	Shih et al., 1980b
	13	0.011-0.150	0.055	0.040	Gordon et al., 1974
	30	0.069-0.28	0.16	0.02	Mroe, 1976
	---	---	0.42	---	Vouk and Piver, 1983
	---	---	0.8[a]	---	Tyndall et al., 1978
	5	0.087-0.4	0.24	---	Suprenant et al., 1980b
Distillate	---	---	0.04	---	Slater and Hall, 1974
	3	0.1-0.21	0.13	---	Suprenant et al., 1980b
Crude	---	0.046-1.11	0.263	0.007	Yen, 1975

[a] Based on weighted average of crude oils used in the U.S.

TABLE 3-6. SUMMARY OF DATA ON ARSENIC IN OIL

Type of Oil	Arsenic Concentration (ppm) Range	Typical Value
Residual #6	0.011-0.8	0.36[a]
Distillate	0.04-0.9	0.085[b]
Crude	0.0024-1.11	0.26[c]

[a] Average of the six studies reported in Table 3-5.

[b] Average of two studies reported in Table 3-5.

[c] Arithmetic mean for oils used in U.S., reported in Yen (1975).

TABLE 3-7. CONCENTRATION OF ARSENIC IN U.S. VERSUS FOREIGN CRUDE OILS

	Range (ppm)	Mean (ppm)	Reference
Foreign	0.01-0.34	0.13	Anderson, 1973
	0.0024-0.284	0.12	Filby and Shaw, 1975
Domestic	0.007-0.61	0.14	Anderson, 1973
	0.65[a]	0.65[a]	Filby and Shaw, 1975
	0.007-0.05	0.02	Cato, 1976

[a] Based on one sample of California crude oil.

TABLE 3-8. CONCENTRATION OF BERYLLIUM IN COAL BY COAL TYPE[a]

Coal Type	Number of Samples	Beryllium Concentration (ppm)	
		Mean	Standard Deviation
Bituminous	3527	2.22	1.66
Subbituminous	640	1.30	1.77
Anthracite	52	1.32	0.85
Lignite	183	1.98	2.71

[a] Data presented in White et al., (1984); based on data in the USGS National Coal Resources Data System (NCRDS) as of 1982. Arithmetic means from this study may be used as typical values for beryllium content of these type of coals.

TABLE 3-9. RANGES OF BERYLLIUM CONCENTRATION IN COALS BY COAL TYPE

Coal Type	Beryllium Concentration Range (ppm)[a]
Bituminous	0.05-25
Subbituminous	0.05-13
Anthracite	NA[b]
Lignite	0.2-15

[a] Lowest and highest values reported in the literature reviewed. Note: The White et al., (1984) study does not list ranges of values in the NCRDS. Valkovic (1983a) provides ranges for bituminous, subbituminous and lignite coals.

[b] NA = not available.

the data. As seen in Table 3-9, the ranges of beryllium concentration are similar between the coal types. The range of beryllium concentrations in bituminous coals is somewhat higher than the other coal types. Because Table 3-8 is based on the NCRDS data base, the most complete data set currently available, the arithmetic means in that table may be considered as typical values for the beryllium content of the four coal types.

Table 3-10 lists the arithmetic mean, standard deviation, and range of beryllium concentration in coal by geographic region. The mean beryllium content varies by a factor of three between the eight geographical regions listed. Again, in some cases, the standard deviation exceeds the mean for beryllium concentration, indicating variability in the data. Nevertheless, the mean beryllium concentration in coals from the Illinois Basin, Appalachian and Interior provinces are the highest among the eight regions listed. The lowest mean beryllium concentration is found in coals from the Alaska region. The means shown in Table 3-10, drawn from the White et al. (1984) study, may be regarded as typical values for beryllium concentration in the coal-producing regions listed, because the White et al. study is based on the NCRDS data base.

Beryllium in Oil-

The reported concentrations of beryllium in oil vary by type of oil and between different studies of the same oil type. As shown in Table 3-11, the reported ranges for beryllium concentration in residual oil vary substantially between different investigators. But with one exception, the means reported agree fairly well. Less data were available with which to characterize the beryllium concentration in distillate and crude oils. The two reported mean concentrations of beryllium in distillate oil vary by a factor of ten. Only one value was found in the literature review identifying a mean concentration of beryllium in crude oil.

Table 3-12 summarizes the data available to characterize beryllium concentrations in different types of oil. The typical values shown in the table are 0.08 ppm for residual oil and 0.05 ppm for distillate. These were obtained by averaging the mean values found in the studies reported in Table 3-11. No data were found to allow comparison of the beryllium content of foreign versus domestic crude oils.

TABLE 3-10. BERYLLIUM CONCENTRATION IN COAL BY REGION

Region	Number of Samples	Beryllium Concentration (ppm) Range	Arithmetic Mean	Standard Deviation	Reference
Appalachian	2749	---	2.27[a]	1.68	White *et al.*, 1984, NCRDS[b]
	331	0.3-7	2	---	Swanson *et al.*, 1976[c]
	29-87	0.1-31	---	---	Valkovic, 1983a[d]
Interior	592	---	2.29[a]	1.6	White *et al.*, 1984, NCRDS
	155	<0.1-5	3	---	Swanson *et al.*, 1976
	47-253	0.7-12	---	---	Valkovic, 1983a
Illinois Basin[e]	82	0.5-4	1.72	---	Ruch *et al.*, 1974
Gulf Province	38	---	2.08[a]	2.85	White *et al.*, 1984, NCRDS
	34	0.2-15	2	---	Swanson *et al.*, 1976
Northern Plains	371	---	1.23[a]	1.86	White *et al.*, 1984, NCRDS
	490	<0.1-15	0.7	---	Hatch and Swanson, 1977
Rocky Mountains	184	---	1.37[a]	1.72	White *et al.*, 1984, NCRDS
	124	0.07-3	0.7	---	Swanson *et al.*, 1976
	174	0.1-31	---	---	Valkovic, 1983a

TABLE 3-10. BERYLLIUM CONCENTRATION IN COAL BY REGION (Continued)

Region	Number of Samples	Beryllium Concentration (ppm)			Reference
		Range	Arithmetic Mean	Standard Deviation	
Alaska	107	---	0.78[a]	0.74	White et al., 1984, NCRDS
	18	0.2-3	0.7	---	Swanson et al., 1976

---

[a] Values are based on most comprehensive data set available and may be used as typical values for beryllium in coal from these regions.

[b] NCRDS = National Coal Resource Data System maintained by USGS.

[c] Data from Swanson et al., (1976) are included in NCRDS. Arithmetic means from the entire NCRDS are more representative then those from Swanson et al., because NCRDS contains data on many more samples. The Swanson data are given to provide an indication of the range of values for beryllium content of coal.

[d] Source reported values for specific states, therefore the number of samples by region is presented as a range.

[e] This is the eastern portion of the Interior province.

TABLE 3-11. CONCENTRATIONS OF BERYLLIUM IN OIL REPORTED IN PREVIOUS STUDIES

Type of Oil	Number of Samples	Beryllium Concentration (ppm) Range	Mean	Standard Deviation	Reference
Residual #6	3	<0.2-<0.15	---	---	Carter et al., 1978
	2	0.1	---	---	Anderson, 1973
	4	<0.0042-0.38	<0.10	---	Suprenant et al., 1980b
	11	<0.0023-<0.4	0.10	1.03	Shih et al., 1980b
	---	---	0.09	---	Slater and Hall, 1974
	---	---	0.0004	---	Vouk and Piver, 1983
	---	---	0.08	---	Anderson, 1973
	---	---	0.08[a]	---	Tyndall et al., 1978
Distillate #2	3	<0.0076-<0.01	<0.0092	---	Suprenant et al., 1980b
	1	---	0.100	---	Castaldini et al., 1981b
Crude	---	---	0.002	---	Vouk and Piver, 1983

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[a] Based on weighted average of crude oil used in U.S.

TABLE 3-12. SUMMARY OF DATA ON BERYLLIUM IN OIL

	Beryllium Concentration (ppm)	
Type of Oil	Range	Typical Value
Residual #6	<0.0023-0.38	0.08[a]
Distillate #2	<0.0076-0.1	0.05[b]
Crude	---	0.002

[a] Average of six means reported in Table 3-11.

[b] Average of two studies reported in Table 3-11.

Cadmium in Fuels

Cadmium in Coal-

As shown in Table 3-13, the mean cadmium concentration in coal varies by coal type, with bituminous coals having the highest mean cadmium concentration. However, the standard deviations for each coal type exceed the means, indicating substantial variability within the data. Table 3-14 lists the ranges of cadmium concentration in four coal types. Bituminous coals have the broadest cadmium concentration range, from less than 0.02 to 100 ppm. The remaining coal types all have cadmium concentration ranges of 0.1 to less than 10 ppm. The means listed in Table 3-13 may be used as representative concentrations of cadmium in each coal type because they were obtained from the NCRDS data base, which is the most comprehensive currently available for coal fuels.

The concentration of cadmium in coal varies distinctly by geographic region. Coals from the Interior Province have a higher (arithmetic) mean cadmium concentration (5.47 ppm) than coals from any other region. Coals from the Illinois Basin, the eastern section of the Interior Province, have a mean cadmium concentration of 2.89 ppm. Coals from other regions have mean cadmium concentrations of less than 1 ppm. The arithmetic means listed in Table 3-15 obtained from the White et al. (1984) analysis of the NCRDS may be used as typical values for cadmium in coal. However, the standard deviations of the mean concentration in each region approach or exceed the mean indicating strong variability within the data.

Cadmium in Oil-

The concentration of cadmium in oil varies by oil type. Table 3-16 presents ranges and means of cadmium concentration in residual, distillate, and crude oil derived from various studies. Table 3-17 summarizes the ranges of cadmium concentration found in the data base for the current study by oil type. Residual and distillate oils have similar cadmium concentration ranges. The mean cadmium concentrations reported for these two oil types are also similar with two exceptions. Two groups of investigators reported mean cadmium concentrations in residual oil of 2.27

TABLE 3-13. CONCENTRATION OF CADMIUM IN COAL BY COAL TYPE[a]

Coal Type	Number of Samples	Cadmium Concentration (ppm)	
		Mean	Standard Deviation
Bituminous	3527	0.91	7.3
Subbituminous	640	0.38	0.47
Anthracite	52	0.22	0.30
Lignite	83	0.55	0.61

[a] Data presented in White et al., (1984); based on data in the USGS National Coal Resources Data System (NCRDS) as of 1982. Arithmetic means from this study may be used as typical values for arsenic content of these types of coals.

TABLE 3-14. RANGES OF CADMIUM CONCENTRATION IN COALS BY COAL TYPE

Coal Type	Cadmium Concentration Range (ppm)[a]
Bituminous	<0.02-100
Subbituminous	0.04-3.7
Anthracite	0.1-0.3
Lignite	<0.11-5.5

[a] Lowest and highest values reported in any of the literature reviewed. Note: The White et al., (1984) study does not list the range of values in the NCRDS. The Swanson et al., (1976) study, which is a subset of the NCRDS describing about 800 coal samples does include ranges for bituminous, and lignite coals. Valkovic, (1983a) provides a range for cadmium concentration in subbituminous coal.

TABLE 3-15. CADMIUM CONCENTRATION IN COAL BY REGION

Region	Number of Samples	Cadmium Concentration (ppm) Range	Arithmetic Mean	Standard Deviation	Reference
Appalachian	2749	---	0.13[a]	0.21	White et al., 1984, NCRDS[b]
	331	0.03-6.8	0.7	---	Swanson et al., 1976[c]
Interior	592	---	5.47[a]	18.5	White et al., 1984, NCRDS
	155	<0.02-100	7.1	---	Swanson et al., 1976
Illinois Basin[d]	82	0.1-65	2.89	---	Ruch, 1974
Gulf Province	38	---	0.50[a]	0.49	White et al., 1984, NCRDS
	34	<0.11-5.5	1.3	---	Swanson et al., 1976
Northern Plains	371	---	0.30[a]	0.48	White et al., 1984, NCRDS
	490	0.02-2.7	0.08	---	Hatch and Swanson, 1977
Rocky Mountains	512	---	0.35[a]	0.38	White et al., 1984, NCRDS
	124	<0.03-0.5	<0.5	---	Swanson et al., 1976
Alaska	107	---	0.28[a]	0.59	White et al., 1984, NCRDS
	18	<0.1-0.7	<0.2	---	Swanson et al., 1976

---

[a] Values are based on the most comprehensive data set currently available and may be used as typical values for cadmium in coal from these regions.

[b] NCRDS = National Coal Resource Data System maintained by USGS.

[c] Data from the Swanson et al., (1976) study are included in the NCRDS. Arithmetic means from the entire NCRDS are more representative than means from Swanson, since the NCRDS contains many more coal samples. The Swanson data are included here to give an idea of the range of values for cadmium content in individual coal samples from each region.

[d] This is the eastern portion of the Interior province.

TABLE 3-16. CONCENTRATION OF CADMIUM IN OIL REPORTED IN PREVIOUS STUDIES

Type of Oil	Number of Samples	Cadmium Concentration (ppm) Range	Mean	Standard Deviation	Reference
Residual #6	5	0.02-<0.94	<0.41	---	Suprenant et al., 1980b
	11	<0.01-0.83	0.30	0.57	Shih et al., 1980b
	3	<0.2-<0.3	---	---	Carter et al., 1978
	---	---	2.27[a]	---	Tyndall et al., 1978
	---	---	2.02	---	Slater and Hall, 1974
	---	0.4-0.5	---	---	Anderson, 1973
Distillate #2	3	<0.01-<0.95	<0.32	---	Suprenant et al., 1980b
	1	---	0.10	---	Castaldini, et al., 1981b
Crude	---	---	0.01	---	Vouk and Piver, 1983
	---	---	0.03	---	Yen, 1975
	---	---	0.05	---	Hofstader et al., 1976

[a] Based on weighted average of crude oil in U.S.

TABLE 3-17. SUMMARY OF DATA FOR CADMIUM IN OIL

Type of Oil	Cadmium Concentration (ppm) Range	Cadmium Concentration (ppm) Typical Value
Residual #6	0.01-2.27	0.3[a]
Distillate #2	0.01- 0.95	0.21[b]
Crude	---	0.03[c]

[a] See text for discussion of this value.

[b] Average of two studies in Table 3-16.

[c] Average of three studies in Table 3-16.

TABLE 3-18. CONCENTRATION OF CADMIUM IN U.S. VERSUS FOREIGN CRUDE OILS

	Range (ppm)	Mean (ppm)	Reference
Foreign	---	0.027[a]	Valkovic, 1978a
	---	0.017[a]	Valkovic, 1978a
	---	0.0015[a]	Valkovic, 1978a
Domestic	---	0.01	Youk and Piver, 1983
	---	0.03	Yen, 1975
	---	0.05	Hofstader *et al.*, 1976

[a] Uncertainty ranges from 10-30 percent.

and 2.00 ppm. Other researchers reported means of less than 0.4 and 0.3 ppm for residual oil and 0.3 and 0.1 ppm for distillate oil. The mean cadmium concentration of crude oil has been reported as 0.01, 0.03, and 0.05 ppm. Typical values for cadmium concentrations in residual, distillate, and crude oil are given in Table 3-17. The suggested typical cadmium content of residual oil is 0.30 ppm and for distillate oil is 0.21 ppm. The typical values for distillate and crude oil were obtained by taking the average of the reported means.

The "typical" value for residual oil, 0.3 ppm, was based on reported concentrations in Table 3-16, without using the two high values, 2.27 and 2.02 ppm. These two values appear to represent the upper end of the data range, compared to other ranges of the concentration of cadmium in residual oil (Table 3-16). An average concentration of 0.3 ppm was reported for cadmium in oil in a study by Shih (1980b). This study included samples taken from utility boilers burning residual oil and it also included more actual data points (11 total) than other studies. Thus, a typical value of 0.3 ppm cadmium in oil is in agreement with one of the more complete data sets available.

Some data were available with which to compare the concentration of cadmium in foreign and domestic crude oils (Table 3-18). Based on these limited data, it appears that domestic and foreign crude oils have about the same cadmium concentration.

Chromium in Fuels

Chromium in Coal-

The mean chromium concentrations in the four primary coal types are shown in Table 3-19. The mean chromium concentration of anthracite coals, 47.2 ppm, is higher than that of the remaining three coal types. Lignite has the lowest mean chromium concentration, 13.5 ppm. However, the standard deviations of the mean for each coal type exceeds the arithmetic mean. This situation indicates that there is a substantial variability in the data. Table 3-20 shows the ranges of chromium concentration in the four coal types. The range for anthracite coals is the highest, 15 to 120 ppm. The

TABLE 3-19. CONCENTRATION OF CHROMIUM IN COAL BY COAL TYPE[a]

Coal Type	Number of Samples	Chromium Concentration (ppm) Mean	Chromium Concentration (ppm) Standard Deviation
Bituminous	3527	20.5	27.5
Subbituminous	640	14.9	25.6
Anthracite	52	47.2	60.9
Lignite	183	13.5	18.2

[a] Data presented in White et al., 1984. Based on data in the USGS National Coal Resources Data System (NCRDS) as of 1982. Arithmetic means from this study may be used as typical values for chromium content of these types of coal.

TABLE 3-20. RANGES OF CHROMIUM CONCENTRATION IN COALS BY COAL TYPE

Coal Type	Chromium Concentration Range (ppm)[a]
Bituminous	<0.5-70
Subbituminous	0.54-70
Anthracite	15-120
Lignite	3-70

[a] Lowest and highest values reported in the literature reviewed. Note: the White et al., (1984) study does not list ranges of values in the NCRDS. The Swanson et al., (1976) study, a subset of NCRDS containing about 800 samples, does list ranges for bituminous and lignite coals. Valkovic, (1983a) lists ranges for subbituminous.

range for the three remaining coal types are similar, with maximum chromium concentrations being 70 ppm. The mean chromium concentrations listed in Table 3-19 may be used as representative concentrations because they are based on the most complete data set currently available (White et al., 1984).

The concentration of chromium in coals from different geographic regions varies by as much as a factor of four. As shown in Table 3-21, coals from the Alaska Province and Western Interior have the highest mean chromium concentrations, 39.7 and 36.9 ppm, respectively. Northern Plains coals have the lowest reported mean chromium concentration, 7.5 ppm. The ranges of chromium concentration in coals from different geographic regions are also shown in Table 3-21. Of interest is the fact that the ranges for chromium concentration in Northern Plains coals extend to 100 ppm while the mean is about 7 ppm. Similarly, the ranges for chromium concentration in Appalachian coals are as high as 400 ppm while the mean is 18.2 ppm. As was true of the analyses of chromium content by coal type, the standard deviations for chromium content by geographic region exceed the mean in all but two cases. Again, this indicates extreme variability in the data.

Chromium in Oil-

Chromium concentration varies between different types of oil. Table 3-22 provides means and ranges for chromium concentration of residual, distillate, and crude oils. Of the three types of oil, distillate oil has the highest reported mean chromium concentration, 1.6 ppm. The reported mean chromium concentrations of residual oil range from 0.070 to 0.9 ppm. The mean concentrations of chromium in crude oil are reported to be 0.0023 to 0.64 ppm. Typical values for chromium in different oil types are shown in Table 3-23 along with a summary of concentration ranges. The typical chromium content of residual oil is 0.40 ppm and the value for distillate oil is 0.95 ppm. The typical values were obtained by taking the average of the means for each oil type reported in the several studies listed in Table 3-22. The apparent conclusion that the typical chromium content of distillate oil is greater than that of residual oil would not be expected and may be a result of the fact the that chromium content of oils is highly variable and few data were available to characterize distillate oil.

TABLE 3-21. CHROMIUM CONCENTRATION IN COAL BY REGION

Region	Number of Samples	Chromium Concentration (ppm)			Reference
		Range	Arithmetic Mean	Standard Deviation	
Appalachian	2749	---	18.2[a]	13.6	White et al., 1984, NCRDS[b]
	331	<0.5-70	20	---	Swanson et al., 1976[c]
	---	8.4-400	---	---	PedCo, 1982
	---	1.5-220	18	---	Valkovic, 1983a
Interior	592	---	27.2[a]	54.1	White et al., 1984, NCRDS
	155	2-70	15	---	Swanson et al., 1976
Illinois Basin[d]	82	4-54	14.1	7.5	Ruch et al., 1974
Gulf Province	38	---	21.2[a]	10.9	White et al., 1984, NCRDS
	34	3-70	20	---	Swanson et al., 1976
Northern Plains	371	---	7.53[a]	12.9	White et al., 1984, NCRDS
	490	0.5-10	5	---	Hatch and Swanson, 1977
	---	0.54-60	6.7	---	Valkovic, 1983a

TABLE 3-21. CHROMIUM CONCENTRATION IN COAL BY REGION (Continued)

Region	Number of Samples	Chromium Concentration (ppm)			Reference
		Range	Arithmetic Mean	Standard Deviation	
Rocky Mountains	512	---	19.7[a]	27.4	White et al., 1984, NCRDS
	124	0.5-70	5	---	Swanson, 1976
	---	0.54-70	11	---	Valkovic, 1983a
Alaska	107	---	39.7[a]	46.9	White et al., 1984, NCRDS
	18	5-70	15	---	Swanson, 1976

---

[a] Values are based on the most comprehensive data set currently available and may be used as typical values for chromium in coal from these regions.

[b] NCRDS = National Coal Resources Data System maintained by USGS.

[c] Data from Swanson et al., (1976) study are included in the NCRDS. Arithmetic means from the NCRDS are more representative than those from Swanson, since the NCRDS contains data on many more coal samples. The Swanson data are included here to provide an indication of the range of values for chromium concentration in coals from these regions.

[d] This is the eastern portion of the Interior province.

TABLE 3-22. CONCENTRATIONS OF CHROMIUM IN OIL REPORTED IN PREVIOUS STUDIES

Type of Oil	Number of Samples	Chromium Concentration (ppm) Range	Mean	Standard Deviation	Reference
Residual #6	4	0.0019-0.073	0.037	0.040	Gordon et al., 1974
	5	0.2-0.5	0.33	---	Suprenant et al., 1980b
	11	0.09-<1.9	0.9	0.46	Shih et al., 1980b
	16	0.026-0.16	0.070	0.050	Mroe, 1976
	9	0.45-1.6	0.79	---	Mroe, 1976
	6	0.33-0.39	0.36	---	Mroe, 1976
	15	0.068-0.77	0.32	---	Mroe, 1976
	3	0.4-<5	---	---	Carter et al., 1978
Distillate #2	3	0.8-2	1.6	---	Suprenant et al., 1980b
	---	---	0.048	---	Cato et al., 1978
	1	---	1.2	---	Castaldini et al., 1981b
Crude	1	---	0.43	---	PedCo, 1982
	---	0.0016-0.017	0.008	---	Yen, 1975
	1	---	0.64	---	PedCo, 1982
	1	---	0.0023	---	PedCo, 1982

TABLE 3-23. SUMMARY OF DATA FOR CHROMIUM IN OIL

	Chromium Concentration (ppm)	
Type of Oil	Range	Typical Value
Residual	0.0019-<5	0.40[a]
Distillate	0.048-2	0.95[b]
Crude	0.0016-0.64	0.27[c]

[a] Average of seven studies in Table 3-22.

[b] Average of three studies in Table 3-22.

[c] Average of four studies in Table 3-22.

Copper in Fuels

Copper in Coal-

The mean concentration of copper in coal does not vary significantly between the four major coal types. Mean copper concentrations range from 14.1 to 18.9 ppm, as shown in Table 3-24. The ranges of copper concentration vary somewhat between the coal types, but most noticeable is the extent of the range of each coal type (Table 3-25). Bituminous coals may contain up to 900 ppm copper and lignite may contain up to 289 ppm. The fact that the standard deviations of the mean copper concentration by coal type approach or exceed their respective means emphasizes the variability of the data. The means listed in Table 3-24 may be viewed as typical or representative values for the concentration of copper in coal because they were derived from the most complete data set currently available.

The concentration of copper in coals from different geographic regions varies by up to a factor of three. Coals from the Gulf Province average about 26 ppm copper, the highest concentration of all regions listed in Table 3-26. The lowest mean copper concentration is found in coals from the Northern Plains Province. The arithmetic means listed in Table 3-26 can be considered as typical values for the concentration of copper in coal from different regions.

Copper in Oils-

The copper concentrations in oil varies with oil type. As shown in Table 3-27 and 3-28, the highest mean copper concentrations are found in residual oil with a range in concentration of up to 79 ppm. The copper concentration of distillate oil ranges from less than 1 to 11 ppm. Crude oil has the lowest reported copper concentration, with a single reported mean of 1.32 ppm. Table 3-28 lists typical values for the copper concentration in oils. The recommended typical values for residual and distillate oil are 5.3 ppm and 5.6 ppm, respectively. These values were determined by taking the average of the means reported in several studies listed in Table 3-27. The reason the value for distillate oil is slightly

TABLE 3-24. CONCENTRATION OF COPPER IN COAL BY COAL TYPE[a]

Coal Type	Number of Samples	Copper Concentration (ppm) Mean	Copper Concentration (ppm) Standard Deviation
Bituminous	3527	17.8	17.8
Subbituminous	640	14.1	14.3
Anthracite	52	18.9	16.4
Lignite	183	17.2	21.2

[a] Data presented in White *et al.*, (1984); based on the USGS National Coal Resources Data System (NCRDS) as of 1982. Arithmetic means reported in this study may be used as typical values for copper content of these coals.

TABLE 3-25. RANGES OF COPPER CONCENTRATION IN COALS BY COAL TYPE

Coal Type	Copper Concentration Range (ppm)[a]
Bituminous	1.2-911
Subbituminous	0.16-120
Anthracite	NA[b]
Lignite	3.3-289

[a] Lowest and highest values reported in the literature reviewed. Note: White *et al.*, (1984) study does not list ranges of values in the NCRDS. The Swanson *et al.*, (1976) data set is a subset of NCRDS containing data on about 800 samples and provides ranges for bituminous and lignite coals. Valkovic (1983a) provides ranges for subbituminous coals.

[b] NA = not available.

TABLE 3-26. COPPER CONCENTRATION IN COAL BY REGION

Region	Number of Samples	Range	Arithmetic Mean	Standard Deviation	Reference
Appalachian	2749	---	18.2[a]	18.2	White et al., 1984, NCRDS[b]
	331	1.2-911	24	---	Swanson et al., 1976[c]
Interior	592	---	17.5[a]	14.6	White et al., 1984, NCRDS
	155	3.7-158	20	---	Swanson et al., 1976
Illinois Basin[d]	82	5-44	14.09	---	Ruch et al., 1974
Gulf Province	38	---	26.5[a]	16.1	White et al., 1984, NCRDS
	34	3.3-289	28	---	Swanson et al., 1976
Northern Plains	371	---	9.82[a]	10.2	White et al., 1984, NCRDS
	---	0.34-76	10.5	---	Hatch and Swanson, 1977
Rocky Mountains	512	---	13.8[a]	16.0	White et al., 1984, NCRDS
	---	1.5-100	9.1	---	Swanson et al., 1976

TABLE 3-26. COPPER CONCENTRATION IN COAL BY REGION (Continued)

Region	Number of Samples	Range	Arithmetic Mean	Standard Deviation	Reference
Alaska	107	---	20.1[a]	16.6	White et al., 1984, NCRDS
	---	8.2-48.8	16.8	---	Swanson et al., 1976

---

[a] Values are based on the most comprehensive data set currently available and may be used as typical values for copper in coal from these regions.

[b] NCRDS = National Coal Resources Data System maintained by USGS.

[c] Data from Swanson et al., (1976) study are included in the NCRDS. Arithmetic means from the NCRDS are more representative than those from Swanson, since the NCRDS contains data on many more coal samples. The Swanson data are included here to provide an indication of the range of values for copper concentration in coals from these regions.

[d] This is the eastern portion of the Interior province.

TABLE 3-27. CONCENTRATIONS OF COPPER IN OIL REPORTED IN PREVIOUS STUDIES

Type of Oil	Number of Samples	Copper Concentration (ppm) Range	Copper Concentration (ppm) Mean	Copper Concentration (ppm) Standard Deviation	Reference
Residual #6	12	ND-0.019[a]	---	---	Gordon et al., 1974
	---	---	0.45	---	Vouk and Piver, 1983
	5	0.8-9.5	3.06	---	Suprenant et al., 19[illegible]b
	11	0.1-79	15	1.17	Shih et al., 1980b
	3	1.5- 3	---	---	Carter et al., 1978
	---	---	2.8[b]	---	Tyndall et al., 1978
	8	0.040-1.7	---	---	Cato et al., 1978
Distillate #2	3	5.5-11	---	---	Suprenant et al., 1980b
	1	11	11	---	Castaldini et al., 1981b
	2	0.056-0.2	0.13	---	Cato et al., 1978
Crude	---	---	1.3	---	Vouk and Piver, 1983
	24	0.03-1.7	---	---	Spaite and Devitt, 1979
	---	0.19-0.93	---	---	Filby and Shah, 1975
	---	0.17-0.1	---	---	Valkovik, 1978
	---	0.1-2.4	---	---	Valkovik, 1978
	---	0.4	---	---	Yen, 1975
	---	0.13-6.33	1.32	---	Yen, 1975

---

[a] ND - not detectable.

[b] Based on weighted average of crude oil used in U.S.

TABLE 3-28. SUMMARY OF DATA ON COPPER IN OIL

	Copper Concentration (ppm)	
Type of Oil	Range	Typical Value
Residual #6	ND-79	5.3[a]
Distillate #2	0.056-11	5.6[b]
Crude	0.03-6.33	1.3[a]

[a] Average of four studies reported in Table 3-27.

[b] Average of the two studies where means were reported in Table 3-27.

[c] Based on two means reported in Table 3-27.

TABLE 3-29. CONCENTRATION OF COPPER IN U.S. VERSUS FOREIGN CRUDE OILS

	Range (ppm)	Mean (ppm)	Reference
Foreign	---	0.19	Filby and Shah, 1975
	---	0.21	Filby and Shah, 1975
Domestic	---	0.93[a]	Filby and Shah, 1975
	---	0.40[b]	Yen, 1975
	0.13-6.33	1.32	Yen, 1975

[a] Based on single sample of California crude oil.

[b] Based on 23 domestic crude oils.

higher than for residual oil may be that there is a lack of representative data to adequately characterize distillate oil. In general, distillate oil will have lower trace metal contents than residual oil.

Some data were available with which to compare the copper concentration in foreign and domestic crude oils (Table 3-29). Based on this limited set of data, domestic oils have a higher concentration of copper than do foreign oils.

Mercury in Fuels

Mercury in Coal-

Table 3-30 presents the mean concentration of mercury in coal by coal type. Bituminous and anthracite coals have the highest mean mercury concentration, 0.21 ppm and 0.23 ppm, respectively. The standard deviation of each mean either approaches or exceeds the mean, indicating strong variations in the data. Table 3-31 shows the ranges of mercury concentration in each of the four coal types. Subbituminous coals have the greatest reported range of mercury concentrations (0.01-8.0 ppm). The means reported by White et al. (1984) in Table 3-30 may be regarded as typical values for mercury concentration in coals because the data were based on the NCRDS, the most comprehensive data set available at this time.

The concentration of mercury in coal also varies by the geographic region from which the coal is obtained. As shown in Table 3-32, coals from the Appalachian and Gulf Provinces have the highest mean mercury concentration, 0.24 ppm for both regions. The lowest mean concentration is found in coals from the Alaska region. The greatest range of mercury concentrations is found in coals from the Alaska region with a reported range of 0.02 ppm to 63 ppm. The means reported by White et al. (1984) may be regarded as typical concentrations of mercury in coals from each geographic region.

Mercury in Oil-

The concentration of mercury in oil depends on the type of oil. As shown in Table 3-33, some reported values for the mean mercury concentration in crude oil are higher than those reported for residual oil. The reported

TABLE 3-30. CONCENTRATION OF MERCURY IN COAL BY COAL TYPE[a]

Coal Type	Number of Samples	Mercury Concentration (ppm) Mean	Mercury Concentration (ppm) Standard Deviation
Bituminous	3527	0.21	0.42
Subbituminous	640	0.10	0.11
Anthracite	52	0.23	0.27
Lignite	183	0.15	0.14

[a] Data presented in White *et al.*, (1984); based on data in the USGS National Coal Resources Data System (NCRDS) as of 1982. Arithmetic means from this study may be used as typical values for arsenic content of these types of coals.

TABLE 3-31. RANGES OF MERCURY CONCENTRATION IN COALS BY COAL TYPE

Coal Type	Mercury Concentration Range (ppm)[a]
Bituminous	<0.01-3.3
Subbituminous	0.01-8.0
Anthracite	0.16-0.30
Lignite	0.03-1.0

[a] Lowest and highest values reported in any of the literature reviewed. Note: The White *et al.*, (1984) study does not list the range of values in the NCRDS. The Swanson *et al.*, (1976) study, which is a subset of the NCRDS describing about 800 coal samples does include ranges for bituminous and lignite coals from certain geographical regions. Valkovic, 1983a lists ranges of mercury concentrations in subbituminous coals.

TABLE 3-32. MERCURY CONCENTRATION IN COAL BY REGION

Region	Number of Samples	Mercury Concentration (ppm) Range	Arithmetic Mean	Standard Deviation	Reference
Appalachian	2749	---	0.24[a]	0.47	White *et al.*, 1984, NCRDS[b]
	331	<0.01-3.3	0.24	---	Swanson *et al.*, 1976[c]
Interior	592	---	0.14[a]	0.14	White *et al.*, 1984, NCRDS
	155	0.01-0.83	0.14	---	Swanson *et al.*, 1976
	---	0.01-1.5	0.15	---	Valkovic, 1983a
Illinois Basin[d]	82	0.03-1.6	0.21	0.22	Ruch, 1974
	---	0.16-1.91	---	---	PedCo, 1982
Gulf Province	38	---	0.24[d]	0.19	White *et al.*, 1984, NCRDS
	34	0.03-1.0	0.18	---	Swanson *et al.*, 1976
Northern Plains	371	---	0.11[a]	0.10	White *et al.*, 1984, NCRDS
	490	0.01-3.8	0.11	---	Hatch and Swanson, 1977
Rocky Mountains	184	---	0.09[a]	0.12	White *et al.*, 1984, NCRDS
	124	0.01-1.48	0.06	---	Swanson *et al.*, 1976
	---	0.01-8.0	0.11	---	Valkovic, 1983a

TABLE 3-32. MERCURY CONCENTRATION IN COAL BY REGION (Continued)

Region	Number of Samples	Mercury Concentration (ppm)			Reference
		Range	Arithmetic Mean	Standard Deviation	
Alaska	107	---	0.08[a]	0.07	White et al., 1984, NCRDS
	18	0.02-63	4.4	---	Swanson et al., 1976

[a] Values are based on the most comprehensive data set currently available and may be used as typical values for mercury in coal from these regions.

[b] NCRDS = National Coal Resource Data System maintained by USGS.

[c] Data from the Swanson et al., (1976) study are included in the NCRDS. Arithmetic means from the entire NCRDS are more representative than means from Swanson, since the NCRDS contains many more coal samples. The Swanson data are included here to give an idea of the range of values for mercury content in individual coal samples from each region.

[d] Eastern section of Interior Province.

TABLE 3-33. CONCENTRATIONS OF MERCURY IN OIL, REPORTED IN PREVIOUS STUDIES

Type of Oil	Number of Samples	Mercury Concentration (ppm) Range	Mean	Standard Deviation	Reference
Residual #6	3	---	<0.1	---	Carter *et al.*, 1978
	---	---	0.02	---	Slater and Hall, 1974
	---	---	10	---	Vouk and Piver, 1983
	---	---	0.04[a]	---	Suprenant *et al.*, 1980b
	11	0.007-0.17	0.066	0.50	Shih *et al.*, 1980a
Distillate #2	1	---	0.40	---	Castaldini *et al.*, 1981b
Crude	---	0.007-0.2	---	---	Anderson, 1973
	1	---	23.1	---	PedCo, 1982
	1	---	0.27	---	PedCo, 1982
	1	---	0.84	---	PedCo, 1982
	43	0.023-30	3.24	---	Yen, 1975

[a] Based on weighted average of crude oils in U.S.

mercury concentrations in crude oil range from 0.023 ppm to 30 ppm, while the range of concentrations in residual oil is 0.007 ppm to 0.17 ppm. Only a single mean value was found in the literature for mercury concentration in distillate oil; therefore, no conclusions can be drawn about the range of mercury in distillate oil. Table 3-34 lists typical values for mercury in oils. These are 0.06 ppm for residual oil and 0.4 ppm for distillate oil. The typical values were obtained by taking the average of the means shown in Table 3-34. The value for distillate oil is the single data point found in the literature and therefore may not be as representative as the values for residual and crude oils.

Table 3-35 compares the concentrations of mercury in foreign crude and domestic crude oils. Based on these data, it appears that domestic crude oils have higher mercury concentrations than foreign crude oils.

Manganese in Fuels

Manganese in Coal-

The mean concentration of manganese in bituminous, subbituminous, and anthracite coals is lower than the concentration in lignite coal. Table 3-36 lists mean values for manganese in these four types of coal based on data from the NCRDS. Although the reported mean concentration for manganese is highest in lignite coals, the range of manganese concentration is higher in bituminous and subbituminous coals (Table 3-37). Bituminous coals may contain as much as 4400 ppm manganese and subbituminous coals as much as 3500 ppm. The means listed in Table 3-36 may be considered typical values for the manganese concentration in the four coal types listed because the values are drawn from the most complete data set currently available, the NCRDS. However, the standard deviations about the means approach or exceed the mean, indicating considerable variability in the data.

Table 3-38 presents mean concentrations and ranges for manganese in coal by geographic region. Generally, coals from the Gulf Province have a higher mean manganese concentration (200 to 300 ppm) than coals from other regions. The upper end of the range of concentrations are highest for coals

TABLE 3-34. SUMMARY OF DATA FOR MERCURY IN OIL

Type of Oil	Mercury Concentration (ppm) Range	 Typical Value
Residual #6	0.007-10	0.06[a]
Distillate #2	---	0.40[b]
Crude	0.007-30	6.86[c]

[a] Average of four studies in Table 3-33; disregarded 10 ppm concentration as an outlier.

[b] Based on single study in Table 3-33. May not be representative.

[c] Average of four studies in Table 3-33.

TABLE 3-35. MERCURY CONCENTRATIONS IN U.S. VERSUS FOREIGN CRUDE OILS

	Range (ppm)	Mean (ppm)	Reference
Foreign	---	0.027	PedCo, 1982
	---	0.084	PedCo, 1982
	---	0.05	Anderson, 1973
	---	0.025	Anderson, 1973
	---	0.006	Anderson, 1973
	---	0.01	Anderson, 1973
	---	0.09	Anderson, 1973
Domestic	0.023-30	3.24	Yen, 1975
	0.007-0.2	---	Anderson, 1973
	---	0.84	PedCo, 1982
	---	0.27	PedCo, 1982
	---	23.1	PedCo, 1982

TABLE 3-36. CONCENTRATION OF MANGANESE IN COAL BY COAL TYPE[a]

Coal Type	Number of Samples	Manganese Concentration (ppm) Mean	Standard Deviation
Bituminous	3527	100	100
Subbituminous	640	100	200
Anthracite	52	100	200
Lignite	183	300	200

[a] Data presented in White et al., (1984); based on data in the USGS National Coal Resources Data System (NCRDS) as of 1982. Arithmetic means from this study may be used as typical values for manganese content of these types of coals.

TABLE 3-37. RANGES OF MANGANESE CONCENTRATION IN COALS BY COAL TYPE

Coal Type	Manganese Concentration Range (ppm)[a]
Bituminous	<3.9-4400
Subbituminous	1.4-3500
Anthracite	20-182
Lignite	7.4-690

[a] Lowest and highest values reported in any of the literature reviewed. Note: The White et al., (1984) study does not list the range of values in the NCRDS. The Swanson et al., (1976) study, containing about 800 coal samples does list ranges for bituminous and lignite coals. Valkovic, 1983a provides a range for manganese in subbituminous coals.

TABLE 3-38. MANGANESE CONCENTRATION IN COAL BY REGION

Region	Number of Samples	Manganese Concentration (ppm) Range	Arithmetic Mean	Standard Deviation	Reference
Appalachian	2749	---	100[a]	100	White et al., 1984, NCRDS[b]
	331	<3.9-1000	620	---	Swanson et al., 1976
	---	0.75-1400	27	---	Valkovic, 1983a
Interior	592	---	100[a]	300	White et al., 1984, NCRDS
	155	4.4-4400	138	---	Swanson et al., 1976
Illinois Basin[d]	82	6-181	53.2	---	Ruch, 1974
	113	6-210	53	41	Gluskoter et al., 1977
Gulf Province	38	---	300[a]	100	White et al., 1984, NCRDS
	34	7.4-690	240	---	Swanson et al., 1976
Northern Plains	371	---	100[a]	100	White et al., 1984, NCRDS
	490	<90-440	50	---	Hatch and Swanson, 1977
	---	7.3-660	75	---	Valkovic, 1983a

TABLE 3-38. MANGANESE CONCENTRATION IN COAL BY REGION (Continued)

Region	Number of Samples	Manganese Concentration (ppm) Range	 Arithmetic Mean	 Standard Deviation	Reference
Rocky Mountains	512	---	100[a]	200	White *et al.*, 1984, NCRDS
	124	3-492	36	---	Swanson *et al.*, 1976
	---	1.4-3500	57	---	Valkovic, 1983a
Alaska	107	---	200[a]	200	White *et al.*, 1984, NCRDS
	18	<16-132	61	---	Swanson *et al.*, 1976

[a] Values are based on the most comprehensive data set currently available and may be used as typical values for manganese in coal from these regions.

[b] NCRDS = National Coal Resource Data System maintained by USGS.

[c] Data from the Swanson *et al.*, (1976) study are included in the NCRDS. Arithmetic means from the entire NCRDS are more representative than means from Swanson, since the NCRDS contains many more coal samples. The Swanson data are included here to give an idea of the range of values for manganese content in individual coal samples from each region.

from the Interior, Rocky Mountain, and Appalachian regions with coals from these areas containing as much as 4400 ppm, 3500 ppm, and 1400 ppm manganese, respectively.

Manganese in Oil-

Crude oil appears to have a higher mean manganese concentration than residual or distillate oils. As shown in Table 3-39, the range of manganese concentrations in crude oil are from 0.63 ppm to 2.54 ppm, with reported mean concentrations of 1.17 ppm and 1.4 ppm. Residual oils have reported mean concentrations higher than distillate oils. Representative values for manganese concentration in residual, distillate, and crude oil are shown in Table 3-40. The typical manganese content of residual oil is 0.49 ppm and that of distillate oil is 0.21 ppm. These values were obtained by calculating the average of the mean concentrations for each oil type shown in Table 3-39.

Some data were available with which to compare the concentration of manganese in domestic and foreign crude oils. Based on these data, domestic crude oils may have manganese concentrations two to three times that of foreign crude oils.

Nickel in Fuels

Nickel in Coal-

The concentration of nickel in coal varies with coal type. Based on data from the NCRDS, anthracite coals appear to have the highest mean nickel concentration of the four major coal types (Table 3-42). Subbituminous and lignite coals have the lowest mean nickel concentrations. Table 3-43 lists the ranges of nickel concentrations in coal by coal type. Of the four types of coal, bituminous coal has the highest absolute nickel concentration, with some samples as high as 300 ppm nickel. The mean nickel concentrations given in Table 3-42 can be considered as typical values for nickel concentration in the four coal types. There is great variability in these data; however, based on the fact that the standard deviations of each mean exceed the mean itself.

TABLE 3-39. CONCENTRATIONS OF MANGANESE IN OIL REPORTED IN PREVIOUS STUDIES

Type of Oil	Number of Samples	Manganese Concentration (ppm) Range	Mean	Standard Deviation	Reference
Residual #6	13	ND-2.3	0.36	0.65	Gordon, 1974
	5	0.1-0.98	0.47	---	Suprenant et al., 1980b
	11	<0.0095-27	0.57	0.58	Shih et al., 1980b
	9	0.24-0.30	0.28	0.06	Mroe, 1976
	6	0.35-0.63	0.48	---	Mroe, 1976
	15	<0.1-0.79	0.41	---	Mroe, 1976
	16	<0.060-2.3	0.36	0.65	Mroe, 1976
	---	---	1.33[a]	---	Tyndall et al., 1978
	---	---	0.16	---	Anderson, 1973
Distillate #2	3	0.25-0.3	0.28	---	Suprenant et al., 1980b
	2	0.052-0.2	0.13	---	Cato et al., 1974
Crude	---	0.63-2.54	1.17	---	Yen, 1975
	---	---	1.4	---	Vouk and Piver, 1983
	---	0.013-1.45[b]	---	---	Anderson, 1973

[a] Based on weighted average of crude oil used in U.S.

[b] Values are means of crude oil from ten states.

TABLE 3-40. SUMMARY OF DATA FOR MANGANESE IN OIL

Type of Oil	Manganese Concentration (ppm) Range	Manganese Concentration (ppm) Typical Value
Residual #6	ND-27[a]	0.49[b]
Distillate #2	0.015-1.45	0.21[c]
Crude	0.63-2.54	1.3[d]

[a] ND = not detectable.

[b] Average of nine studies in Table 3-39.

[c] Average of two studies reported in Table 3-39.

[d] Average of two studies in Table 3-39.

TABLE 3-41. CONCENTRATION OF MANGANESE IN U.S. VERSUS FOREIGN CRUDE OILS

	Range (ppm)	Mean (ppm)	Reference
Foreign	---	0.79	Valkovic, 1983a
	---	0.21	Valkovic, 1983a
	---	0.048	PedCo, 1982
Domestic	0.63-2.54	1.17	Yen, 1975
	---	1.4	Vouk and Piver, 1983
	0.013-1.45[a]	---	Anderson, 1973

[a] Values are means for crude oils from ten states.

TABLE 3-42. CONCENTRATION OF NICKEL IN COAL BY COAL TYPE[a]

Coal Type	Number of Samples	Nickel Concentration (ppm) Mean	Nickel Concentration (ppm) Standard Deviation
Bituminous	3527	16.9	19.2
Subbitumious	640	7.02	8.44
Anthracite	52	28.5	32.0
Lignite	183	8.35	19.7

[a] Data presented in White et al., (1984); based on data in the USGS National Coal Resources Data System (NCRDS) as of 1982. Arithmetic means from this study may be used as typical values for nickel content of these types of coals.

TABLE 3-43. RANGES OF NICKEL CONCENTRATION IN COALS BY COAL TYPE

Coal Type	Nickel Concentration Range (ppm)[a]
Bituminous	1.5->300
Subbituminous	0.32-69
Anthracite	17-50
Lignite	3-70

[a] Lowest and highest values reported in any of the literature reviewed. Note: The White et al., (1984) study does not list the range of values in the NCRDS. The Swanson et al., (1976) study, which is a subset of the NCRDS describing about 800 coal samples, does include ranges for bituminous and lignite coals from certain geographical regions. Valkovic (1983a) lists ranges for nickel concentration in subbituminous coals.

Coals from the Interior Province and some parts of the Appalachian Province have higher mean nickel concentrations than coals from other regions. Table 3-44 presents (arithmetic) mean concentrations and ranges of concentrations of nickel in coals from seven geographical regions. Lowest mean nickel concentrations are reported for coals from the Northern Plains and Rocky Mountain Provinces. But coals from these areas also show a wide range of nickel concentrations, up to 300 ppm for coals from the Northern Plains and 340 ppm for coals from the Rocky Mountain province. The mean concentrations shown in Table 3-44 from the White et al. (1984) study can be viewed as typical or representative values for the nickel concentration in coal from the geographic regions listed. Again, the standard deviations about each mean are large, indicating considerable variability in the data.

Nickel in Oil-

In relative comparison to the other trace elements under study, fuel oils contain large amounts of nickel. The concentration of nickel in oil varies significantly by oil type. Table 3-45 shows that crude oil may contain over 300 ppm nickel while residual oil usually contains 6 ppm to 70 ppm. Distillate oil contains less nickel, 1 ppm to 18 ppm. Table 3-46 summarizes the range of nickel concentrations in oil by oil type and shows a typical mean value. The typical values (24.0 ppm for residual oil and 3.38 ppm for distillate oil) were obtained by taking the average of the means reported for each oil type in Table 3-45. The typical value for nickel concentration in crude oil is significantly higher than that for residual and distillate oils.

Table 3-47 gives mean nickel concentrations for foreign and domestic crude oils. The data are widely scattered for both foreign and domestic crudes. The reported means for foreign crudes range from less than 1 ppm to 117 ppm nickel and 2.4 ppm to 165.8 ppm in domestic crudes.

Lead in Fuels

The concentration of lead in coal from the U. S. ranges from <1 to 33 ppm, although some coals have been found to contain over 250 ppm lead (U. S. Environmental Protection Agency, 1985). The weighted average lead

TABLE 3-44. NICKEL CONCENTRATION IN COAL BY REGION

Region	Number of Samples	Nickel Concentration (ppm) Range	Arithmetic Mean	Standard Deviation	Reference
Appalachian	2749	---	15.4[a]	14.7	White *et al.*, 1984, NCRDS[b]
	331	1.5->300	15	---	Swanson *et al.*, 1976c
Interior	592	---	26.7[a]	32.6	White *et al.*, 1984, NCRDS
	155	1-200	30	---	Swanson *et al.*, 1976
	---	0.87-580	26	---	Valkovic, 1983a
Illinois Basin[d]	82	8-68	22.4	10.8	Ruch, 1974
Gulf Province	38	---	14.0[a]	13.0	White *et al.*, 1984, NCRDS
	34	3-70	20	---	Swanson *et al.*, 1976
Northern Plains	371	---	5.33[a]	9.67	White *et al.*, 1984, NCRDS
	490	<0.5-300	5	---	Hatch and Swanson, 1977
Rocky Mountains	184	---	6.71[a]	8.19	White *et al.*, 1984, NCRDS
	124	0.7-20	3	---	Swanson *et al.*, 1976
	---	0.35-340	6.5	---	Valkovic, 1983

TABLE 3-44. NICKEL CONCENTRATION IN COAL BY REGION (Continued)

Region	Number of Samples	Nickel Concentration (ppm) Range	Arithmetic Mean	Standard Deviation	Reference
Alaska	107	---	11.2[a]	8.8	White et al., 1984, NCRDS
	18	2-30	10	---	Swanson et al., 1976

[a] Values are based on the most comprehensive data set currently available and may be used as typical values for nickel in coal from these regions.

[b] NCRDS = National Coal Resource Data System maintained by USGS.

[c] Data from the Swanson et al., (1976) study are included in the NCRDS. Arithmetic means from the entire NCRDS are more representative than means from Swanson, since the NCRDS contains many more coal samples. The Swanson data are included here to give an idea of the range of values for nickel content in individual coal samples from each region.

[d] Eastern segment of Interior Basin.

TABLE 3-45. CONCENTRATIONS OF NICKEL IN OIL REPORTED IN PREVIOUS STUDIES

Type of Oil	Number of Samples	Nickel Concentration (ppm)			Reference
		Range	Mean	Standard Deviation	
Residual #6	5	10-73	26.2	---	Suprenant _et_ _al._, 1980b
	9	14-21	17	---	Mroe, 1976
	6	10-20	15	---	Mroe, 1976
	15	13-24	17	---	Mroe, 1976
	11	6-51	19	0.54	Shih _et_ _al._, 1980b
	---	---	50.07	---	Slater and Hall, 1974
Distillate #2	3	1-18	6.67	---	Suprenant _et_ _al._, 1980b
	1	---	0.09	---	Castaldini _et_ _al._, 1981b
	2	0.15-1.7	---	---	Cato _et_ _al._, 1974
Crude	24	0.3-35	---	---	Spaite and Devitt, 1979
	---	49.1-344.5	165.8	---	Yen, 1975
	1	---	98.4	---	PedCo, 1982
	1	---	49.1	---	PedCo, 1982
	1	---	117	---	PedCo, 1982
	1	---	0.6	---	PedCo, 1982
	---	1.4-4.3	2.4	---	Anderson, 1973

TABLE 3-46. SUMMARY OF DATA FOR NICKEL IN OIL

Type of Oil	Nickel Concentration (ppm) Range	 Typical Value
Residual #6	6-73	24.0[a]
Distillate #2	0.15-18	3.38[b]
Crude	0.3-344.5	72.2[c]

[a] Average of six studies in Table 3-45.

[b] Average of two studies in Table 3-45.

[c] Average of six studies in Table 3-45.

TABLE 3-47. NICKEL CONCENTRATION IN U.S. VERSUS FOREIGN CRUDE OILS

	Range (ppm)	Mean (ppm)	Reference
Foreign	---	44.1	Anderson, 1973
	---	8.8	Anderson, 1973
	---	59	Anderson, 1973
	---	117	PedCo, 1982
	---	0.609	PedCo, 1982
Domestic	0.3-35	---	Spaite and Devitt, 1979
	49.1-344.5	165.8	Yen, 1975
	1.4-4.3	2.4	Anderson, 1973
	---	93.5	Filby and Shah, 1975

concentration in coal from the U. S. has been reported as 8.3 ppm (U. S. Environmental Protection Agency, 1985). In the derivation of emission factors in this report for lead from coal combustion, an average of 8.3 ppm lead was used for bituminous coal and 8.1 ppm for anthracite coal (U. S. Environmental Protection Agency, 1985).

The limited data base used to determine the concentration of lead in oil reported that the lead content of residual oil averaged about 1 ppm and ranged from 0.1-0.5 ppm for distillate oil (U. S. Environmental Protection Agency, 1985). The derivation of emission factors for lead from oil combustion in this report were based on a lead concentration of 1 ppm in residual oil. For distillate oil, the average of the reported range of lead concentrations, 0.3 ppm (0.1-0.5 ppm), was used.

Thorium in Coal

The concentration of thorium in coal does not vary significantly by coal type. Table 3-48 shows that mean thorium concentrations range from about 3 ppm in bituminous coals to 7 ppm in lignite. The ranges of thorium concentration do vary by coal type, as seen in Table 3-49. Bituminous coals can contain as much as 79 ppm thorium while the highest value found (in the literature reviewed) for anthracite is about 14 ppm. The mean concentrations listed in Table 3-48 can be regarded as representative of the thorium concentration in coal by coal type. These values are based on data from the NCRDS, the most complete data set available.

The concentration of thorium in coals varies somewhat by geographical region. Table 3-50 shows that coals from the Gulf Province have a somewhat higher concentration of thorium than do coals from other regions. The means reported by White et al. (1984) may be regarded as typical values for thorium concentration in coals from these regions.

Of special interest is the concentration of some radioactive isotopes of thorium in coal. Table 3-51 lists mean concentrations of thorium-232 in coals from several States and one region. Of the States for which data were available, coals from Pennsylvania have the highest mean thorium-232 concentration, 0.4 picoCuries per gram (pCi/g).

TABLE 3-48. CONCENTRATION OF THORIUM IN COAL BY COAL TYPE[a]

Coal Type	Number of Samples	Thorium Concentration (ppm) Mean	Thorium Concentration (ppm) Standard Deviation
Bituminous	3527	3.03	3.15
Subbituminous	640	5.13	4.64
Anthracite	52	6.09	2.92
Lignite	183	7.13	5.70

[a] Data presented in White et al., 1984; based on data in the USGS National Coal Resources Data System (NCRDS) as of 1982. Arithmetic means from this study may be used as typical values for thorium content of these types of coals.

TABLE 3-49. RANGES OF THORIUM CONCENTRATION IN COALS BY COAL TYPE

Coal Type	Thorium Concentration Range (ppm)[a]
Bituminous	2.2-79
Subbituminous	<3-18
Anthracite	2.8-14.4
Lignite	<3-28.4

[a] Lowest and highest values reported in any of the literature reviewed. Note: The White et al., (1984) study does not list the range of values in the NCRDS. The Swanson et al., (1976) study, a subset of the NCRDS describing about 800 coal samples, does include ranges. This table is based on the Swanson work.

TABLE 3-50. THORIUM CONCENTRATION IN COAL BY REGION

Region	Number of Samples	Thorium Concentration (ppm) Range	Thorium Concentration (ppm) Arithmetic Mean	Thorium Concentration (ppm) Standard Deviation	Reference
Appalachian	2749	---	2.98[a]	2.33	White et al., 1984, NCRDS[b]
	331	2.2-47.8	4.9	---	Swanson et al., 1976[c]
Interior	592	---	3.73[a]	6.60	White et al., 1984, NCRDS
Illinois Basin[d]	56	0.71-5.1	2.1	0.87	Gluskoter et al., 1977
Gulf Province	38	---	8.96[a]	6.33	White et al., 1984, NCRDS
	34	<3-28.4	8.3	---	Swanson et al., 1976
Northern Plains	371	---	4.30[a]	3.74	White et al., 1984, NCRDS
	93	<2-8.0	2.7	---	Swanson et al., 1976
Rocky Mountains	512	---	5.13[a]	4.65	White et al., 1984, NCRDS
	134	<3-34.8	3.6	---	Swanson et al., 1976
Alaska	107	---	3.49[a]	2.54	White et al., 1984, NCRDS
	18	<3-18	4.4	---	Swanson et al., 1976

[a] Values are based on the most comprehensive data set currently available and may be used as typical values for thorium in coal from these regions.

[b] NCRDS = National Coal Resource Data System maintained by USGS.

[c] Data from the Swanson et al., (1976) study are included in the NCRDS. Arithmetic means from the entire NCRDS contains data for many more coal samples. The Swanson data are included here to give a indication of the range of values for thorium content in individual coal samples from each region.

[d] Eastern portion of Interior Basin.

TABLE 3-51. CONCENTRATION OF THORIUM-232 IN COAL BY STATE OR REGION

State/Region[a]	Number of Samples	Thorium-232 Concentration (pCi/g) Range	Thorium-232 Concentration (pCi/g) Mean	Reference
---	910	0.1-5.3	0.50	Beck and Miller, 1980
Illinois	3	0.11-0.21	0.15	Beck *et al.*, 1980
Wyoming	1	---	0.291	Office of Radiation Programs, 1979
Colorado	3	0.385-0.493	0.423	Office of Radiation Programs, 1979
Kentucky	2	0.198-0.402	0.3	Office of Radiation Programs, 1979
Pennsylvania	---	---	0.40	Beck *et al.*, 1980
Appalachian	---	---	0.43	Beck *et al.*, 1980

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[a] A comprehensive data set of thorium-232 concentrations in coal by region or coal type was not found in the literature searched. The data presented here provides an indication of the concentration of thorium-232 in coal samples in different states.

Uranium in Coal

The data presented in Table 3-52 indicate that the uranium content of the four major coal types does not vary significantly. However, lignite coals have a slightly higher mean uranium concentration than the remaining three coal types. Bituminous and subbituminous coals have a wider reported range of uranium concentrations, up to 59 and 76 ppm for these two coal types, respectively. The means listed in Table 3-53 may be viewed as typical values for uranium in coal because they are based on the most complete data set currently available. However, the standard deviations about the means are greater than the means themselves, indicating variability in the data set.

Table 3-54 lists means and ranges of uranium in coal by geographic region. There is not a large difference in mean uranium concentrations among coals from these regions. But coal from the Western Interior and the Gulf Province have higher mean concentrations of uranium than do coals from other regions. The means listed in the table can be regarded as typical for coal from each region.

The uranium-238 concentrations in coal from five states and one region are given in Table 3-55. Highest uranium-238 concentrations are seen in coals from Kentucky and Colorado, 0.91 and 0.877 pCi/g, respectively.

BEHAVIOR OF TOXIC POLLUTANTS DURING COMBUSTION

Trace metals contained in fuels are released during the combustion process. They may be retained in the bottom ash, or they may be emitted via the flue gas. Trace elements present in flue gas may be contained in the fly ash or they may be in vapor form. Polycyclic organic matter (POM) is also formed during combustion and emitted to the atmosphere. This section describes the behavior of trace metals and radionuclides during combustion processes and discusses the formation/transformation of POMs and formaldehyde.

TABLE 3-52. CONCENTRATION OF URANIUM IN COAL BY COAL TYPE[a]

Coal Type	Number of Samples	Uranium Concentration (ppm) Mean	Uranium Concentration (ppm) Standard Deviation
Bituminous	3527	1.85	2.71
Subbituminous	640	2.13	3.84
Anthracite	52	1.94	3.38
Lignite	183	3.37	10.3

[a] Data presented in White et al., 1984; based on data in the USGS National Coal Resources Data System (NCRDS) as of 1982. Arithmetic means from this study may be used as typical values for uranium in coal.

TABLE 3-53. RANGES OF URANIUM CONCENTRATION IN COALS BY COAL TYPE

Coal Type	Uranium Concentration Range (ppm)[a]
Bituminous	<0.2-59
Subbituminous	0.4-76
Anthracite	0.3-25.2
Lignite	0.5-16.7

[a] Lowest and highest values reported in the literature reviewed. Note: The White et al., (1984) study does not list the range of values in the NCRDS. The Swanson et al., (1976) study, a subset of the NCRDS containing data on about 800 coal samples does provide ranges. This table is based primarily on the Swanson et al., (1976) study and Valkovic, (1983a).

TABLE 3-54. URANIUM CONCENTRATION IN COAL BY REGION

Region	Number of Samples	Uranium Concentration (ppm) Range	Arithmetic Mean	Standard Deviation	Reference
Appalachian	2749	---	1.66[a]	1.87	White et al., 1984, NCRDS[b]
	331	<0.2-10.5	1.4	---	Swanson et al., 1976[c]
	---	0.1-19	1.6	---	Valkovic, 1983a
Interior	592	---	2.98[a]	5.07	White et al., 1984, NCRDS
	---	0.20-59	3.2	---	Valkovic, 1983a
Illinois Basin[d]	56	0.31-4.6	1.5	---	Swanson et al., 1976
Gulf Province	38	---	3.07[a]	2.64	White et al., 1984, NCRDS
	34	0.5-16.7	3.2	---	Swanson et al., 1984
Northern Plains	371	---	1.59[a]	2.24	White et al., 1984, NCRDS
	93	<0.2-2.9	0.9	---	Swanson et al., 1976
Rocky Mountains	512	---	2.40[a]	4.40	White et al., 1984, NCRDS
	134	<0.2-23.8	1.6	---	Swanson et al., 1976
	---	0.06-76	2.8	---	Valkovic, 1983a

TABLE 3-54. URANIUM CONCENTRATION IN COAL BY REGION (Continued)

Region	Number of Samples	Uranium Concentration (ppm) Range	Arithmetic Mean	Standard Deviation	Reference
Alaska	107	---	1.28[a]	1.43	White et al., 1984, NCRDS
	18	0.4-5.2	1.2	---	Swanson et al., 1976

[a] Values are based on the most comprehensive data set currently available and may be used as typical values for uranium in coal from these regions.

[b] NCRDS = National Coal Resource Data System maintained by USGS.

[c] Data from the Swanson et al., (1976) study are included in the NCRDS. Arithmetic means from the entire NCRDS are more representative than means from Swanson, since the NCRDS contains many more coal samples. The Swanson data are included here to give an idea of the range of values for uranium content in individual coal samples from each region.

TABLE 3-55. CONCENTRATION OF URANIUM-238 IN COAL BY STATE OR REGION

State/Region[a]	Number of Samples	Uranium-238 Concentration (pCi/g) Range	Mean	Reference
---	910	0.1-15	0.60	Beck and Miller, 1980
Wyoming	4	---	0.42	Beck *et al.*, 1980
Montana	---	---	<0.1	Beck *et al.*, 1980
Illinois	3	---	0.61	Beck *et al.*, 1980
Colorado	3	0.780-0.983	0.877	Office of Radiation Programs, 1979
Kentucky	2	0.660-1.16	0.91	Office of Radiation Programs, 1979
Appalachian Region	---	---	0.80	Beck *et al.*, 1980

[a] A comprehensive data set providing information on uranium-238 concentrations in coal by region or coal type was not found in the literature searched. The data presented here provide an indication of the uranium-238 concentrations in coals from different states in the U.S.

Partitioning and Enrichment Behavior of Trace Metals during Combustion

The concepts of partitioning and enrichment are frequently used to characterize the behavior of trace elements in combustion processes. Partitioning generally refers to the split of the trace element among the various boiler outlet streams: bottom ash, fly ash, and flue gas. Enrichment refers to the difference in trace element concentration between different streams or to the change in trace element concentration of bottom ash or fly ash as a function of particle size.

One method of describing partitioning behavior is by reporting the fraction of the total elemental mass input that leaves the boiler via each of the outlet streams. Another method is to compare the trace element concentration of one outlet stream to that of another through enrichment ratios (or enrichment factors). In general, enrichment ratios are calculated by the following equation:

$$ER_{ij} = \frac{C_{ij}/C_{Rj}}{C_{ic}/C_{Rc}}$$

where

ER_{ij} = enrichment ratio for element i in stream j
C_{ij} = concentration of element i in stream j
C_{Rj} = concentration of reference element R in stream j
C_{ic} = concentration of element i in fuel
C_{Rc} = concentration of reference element R in fuel

An enrichment ratio greater than 1 indicates that the element is "enriched" in the given stream, or, expressed another way, that the element "partitions" to the given stream. Different reference elements commonly used by various authors are aluminum, iron, scandium, and titanium. These elements are chosen because their partitioning and enrichment behavior is often comparable to that for the total mass. That is, their concentration by weight in all ash streams and size fractions is constant.

Various classification schemes have been developed to describe partitioning or enrichment behavior (Klein, et al., 1975b; Coles et al., 1979; Baig et al., 1981). The classification scheme used by Baig et al. (1981) is as follows:

- Class 1. Elements which are approximately equally distributed between fly ash and bottom ash, or show little or no small particle enrichment.
- Class 2. Elements which are enriched in fly ash relative to bottom ash, or show increasing enrichment with decreasing particle size.
- Class 3. Elements which are intermediate between Classes 1 and 2.
- Class 4. Elements which are emitted in the gas phase.

Because of factors such as differences in classification schemes used by different investigators, different and ill-defined dividing lines between the classes, sampling and analytical errors in the data used to determine classification, and variations in the behavior of an element in different studies, it is not possible to make an absolute classification of the elements. However, such a classification scheme is useful in indicating general trends in the behavior of the elements. Several of the elements have shown behavior characteristics of each of the first three classes in different studies. These elements were assigned to Class 3, since Classes 1 and 2 represent the extremes in behavior and Class 3 is intermediate between them.

Based on information in about 20 previous studies, Baig et al. (1981) classified arsenic and cadmium as Class 2 elements. Beryllium, chromium, manganese, and nickel were placed in Class 3. Copper was not included in the Baig et al. (1981) study, but may also be placed in Class 3. Mercury behaved as a Class 4 element. Brief descriptions of the behavior of each element follow:

As. Arsenic has exhibited Class 2 behavior in almost every study. Therefore, As is considered to be a Class 2 element (Baig et al., 1981).

Be. Beryllium has exhibited Class 1 behavior in some studies, Class 2 in others, and Class 3 in others. This difference in classification could be due in part to differences in criteria used to assign elements to one class over another, or could be due to differences in the behavior of Be in different combustion systems. For this study, Be is considered as a Class 3 element (Baig et al., 1981).

Cd. Cadmium has exhibited Class 2 behavior in every study examined, and is therefore considered to be a Class 2 element (Baig et al., 1981).

Cr. Chromium, like Be, has shown Class 1, 2, and 3 behavior in different studies, and is considered as a Class 3 element (Baig et al., 1981).

Cu. Copper has shown Class 2 behavior in most studies (Klein et al., 1975b; Mann et al., 1978; Radian Corporation, 1975a; Cowherd, 1975). However, Class 1 and 3 behavior has also been reported (Davison et al., 1974; Natusch et al., 1974; Coles et al., 1979). Copper is considered a Class 3 element, but resembles Class 2 more closely than the other Class 3 elements do.

Mn. Manganese has also shown Class 1, 2, and 3 behavior, and will be considered as a Class 3 element. However, since it has been reported to show Class 1 behavior more frequently and Class 2 behavior less frequently than the other Class 3 elements, it may come closer to Class 1 behavior than to Class 2 and resemble Class 1 elements more than the other Class 3 elements do (Baig et al., 1981).

Ni. Nickel has shown Class 1, 2, and 3 behavior, and will be considered as a Class 3 element (Baig et al., 1981).

Hg. Mercury is a Class 4 element at normal stack temperature of 150°C (300°F). Lower temperatures, however, will cause condensation of some of the gaseous mercury so that it can be considered as Class 2 (Baig et al., 1981).

Theories Explaining Trace Metal Behavior in Coal Combustion Systems-

Volatilization/condensation mechanism. One of the most widely held, fundamental theories that has been proposed to explain the behavior of trace elements in coal combustion systems is the volatilization/condensation mechanism (VCM). This theory suggests that volatile species in the ash are vaporized in the firebox, where peak temperatures of 1650°C (3000°F) are typical for pulverized coal-fired boilers. As the flue gas cools to 370-430°C (700-800°F) in the convective heat transfer section and further to 150°C (300°F) in the air preheater, the volatilized species condense. These species may condense or adsorb onto existing particles according to the available surface area or they may condense homogeneously, forming fine particles. The elements thus volatilized would be depleted in the bottom ash and concentrated in the fly ash, since the fly ash has more relative surface area than the bottom ash and since the bottom ash does not come in contact with the volatilized elements long enough for the elements to condense on the bottom ash (Baig et al., 1981).

The VCM primarily explains the behavior of the Class 2 elements, but it also explains the behavior of the other classes of elements. The Class 1 elements are the nonvolatile matrix elements that do not vaporize in the boiler. These elements form the fly ash matrix on which the volatilized elements condense. The Class 1 elements are thus equally distributed between bottom ash and fly ash, and show no small particle enrichment. The Class 3 elements apparently are partially vaporized in the boiler, and thus show behavior intermediate between Classes 1 and 2. The Class 4 elements are highly volatile. They do not condense or condense only partially as the flue gas cools to normal stack temperature (Baig et al., 1981).

The VCM also explains the enrichment of Class 2 elements on small particle sizes. Because smaller particles have a higher surface area, relative to their mass, than the larger particles, they have more available area on which Class 2 and 3 elements can condense. The Class 1 elements are not vaporized, and thus show no dependence of concentration on particle size.

Compound boiling points. Kaakinen et al. (1975) have compared enrichment ratios for several elements to various measures of element volatility, including melting points, boiling points, and vapor pressures of elemental and oxide forms, and reported that the oxide properties generally showed good agreement.

All of the Class 2 and Class 4 elements included in the current study (As, Cd, and Hg) have elemental or oxide boiling points less than 1650°C (3000°F). Class 1 elements, such as Al, have boiling points greater than 1650°C (3000°F). The Class 3 elements also generally have elemental and oxide boiling points greater than 1650°C (3000°F), and so would be expected to behave like the Class 1 elements.

A simple correlation of the element or oxide boiling points thus does not explain the behavior of all trace elements. A fraction of these elements, however, may form compounds other than oxides (such as chlorides or carbonyls) that are volatile. Reducing conditions can exist during the initial combustion stage that might contribute to the formation of such compounds. Moreover, the compounds formed and the fractions of the element forming the volatile and nonvolatile compounds might vary under different combustion systems and different conditions of furnace temperature, coal time/temperature history, excess air, and coal composition. Such variations could explain the observed variation in the behavior of these elements in different combustion systems (Baig et al., 1981).

Elemental association in coal. The association of trace elements in coal (with the organic fraction or inorganic matrix) has also been suspected of playing a key role in the fate of elements upon combustion (Mann et al., 1978; Edwards et al, 1980a). The theory is that trace elements bound in the organic phase are atomized during combustion, while those occluded with the mineral matter in the coal are less likely to be vaporized. Moreover, actual volatilization of the organically associated elements may not be necessary for trace element enrichment. Deposition of the nonvolatilized trace elements associated with the organic fraction, on the remaining mineral inclusions that form the fly ash, will give a similar inverse dependence of concentration with size. This theory may explain the behavior of certain elements, but not all (Baig et al., 1981)..

Theories Explaining Trace Metal Behavior in Oil Combustion Systems-

Since no bottom ash is formed from oil combustion, it can generally be assumed that all of the trace elements present in the oil are emitted with the fly ash or in the gas phase. There are few data on particle size association of trace metals emitted from oil combustion systems. Volatilization/condensation mechanisms may play a role in the behavior of elements in oil combustion systems. However, oil fly ash particles have irregular, honeycombed surfaces as opposed to coal fly ash particles which have smooth, round surfaces. Therefore, surface area will not necessarily have a strong dependence on particle size, and trace metal enrichment on small particles may not be as pronounced for oil combustion as for coal combustion (Baig et al., 1981).

Behavior of Radionuclides During Combustion

Naturally occurring radionuclides present in coal include uranium-238 (U-238), uranium-235 (U-235), thorium-232 (Th-232), and potassium-40 (K-40) as well as their daughter products. Some of these include Th-230, Th-228, radon-228 (R-228), R-226, lead-210 (Pb-210) and polonium 210 (Po-210). For the purposes of this study, U-238 and Th-232 will be used as indicators of radionuclide emissions. These two species have the longest half-lives (4.5×10^9 years for U-238 and 1.4×10^{10} years for Th-232) and are the parent species of the two predominant decay chains. They have been selected as indicators of radionuclides in previous risk assessments (Environmental Research and Technology, Inc., 1983; U. S. Environmental Protection Agency, 1984a).

Radioactive uranium and thorium contained in the coal feed is partitioned between the bottom ash and fly ash during combustion. Very little, if any, radionuclides are emitted to the atmosphere in vapor form (Roeck et al., 1983)

Several studies have found that U-238 is enriched in the small (<1 um diameter) fly ash particles (Coles et al., 1978; Klein et al., 1975b; Roeck et al., 1983). Uranium-238 would be termed a Class 2 element using the terminology developed previously. It has been postulated that a portion of the uranium in coal is associated with the silicate (i.e., coffinite) and follows the alumino-silicate minerals which melt and drop out as slag during the combustion process. Another fraction of the U-238 is dispersed in the coal as uranite and becomes volatile as uranium oxide (UO_3) during combustion and continues along with the flue gas and fly ash. At normal stack temperatures the UO_3 condenses out on the fly ash, preferentially concentrating on the smaller fly ash particles because of their larger surface area to mass ratio (Coles et al., 1978).

Some studies have found that for Th-232, there is little preferential partitioning between the slag and the collected or discharged fly ash (Coles et al., 1978; Klein et al., 1975b). Other studies have indicated small particle enrichment in the fly ash (Roeck et al., 1983). Thorium-232 would be termed a Class 3 element using the terminology developed in previously.

Formation and Transformation of POM and Formaldehyde During Combustion

Formaldehyde-

Formaldehyde is formed and emitted during combustion of hydrocarbon-based fuels such as coal and oil. Formaldehyde is present in the vapor phase of the flue gas. Since formaldehyde is subject to oxidation and decomposition at the high temperatures encountered during combustion, large units with efficient combustion resulting from closely regulated air-fuel ratios, uniformly high combustion chamber temperatures, and relatively long retention times should have lower formaldehyde emission rates than do small, less efficient combustion units (Hangebrauck et al., 1964; Rogozen et al., 1984b).

Polycyclic Organic Matter-

The term polycyclic organic matter (POM) defines a broad class of compounds which generally includes all organic structures having two or more fused aromatic rings (i.e., rings which share a common border). Polycyclic organic matter with up to seven fused rings have been identified. Theoretically, millions of POM compounds could be formed; however, the list of species that have been identified and studied is more on the order of approximately 100 (U. S. Environmental Protection Agency, 1980b).

Nine major categories of compounds have been defined by the U. S. Environmental Protection Agency to constitute the class known as POM (Shih et al., 1980a). The nine categories are as follows.

1. Polycyclic aromatic hydrocarbons (PAHs) - the PAHs include naphthalene, phenanthrene, anthracene, fluoranthene, acenaphthalene, chrysene, benzo(a)anthracene, cyclopenta(c,d)pyrene, the benzpyrenes, indeno(1,2,3-c,d)pyrene, benzo(g,h,i)perylene, coronene, and some of the alkyl derivatives of these compounds.
2. Aza arenes - aza arenes are aromatic hydrocarbons containing a ring nitrogen.
3. Imino arenes - these are aromatic hydrocarbons containing a ring nitrogen with a hydrogen.
4. Carbonyl arenes - these are aromatic hydrocarbons containing one ring carbonyl group.
5. Dicarbonyl arenes - also known as quinones, contain two ring carbonyl groups.
6. Hydroxy carbonyl arenes - these are ring carbonyl arenes containing hydroxy groups and possibly alkoxy or acyloxy groups.
7. Oxa arenes and thia arenes - oxa arenes contain a ring oxygen atom, while thia arenes contain a ring sulfur atom.
8. Polyhalo compounds - these include the polychlorinated dibenzo-p-dioxin (PCDDs), polychlorinated dibenzofurans (PCDFs), and polychlorinated biphenyls (PCBs), and also brominated analogs of these compounds such as polybrominated biphenyls (PBBs).
9. Pesticides - including aldrin, chlordane, and DDT.

These categories were developed to better define and standardize the types of compounds considered to be POM.

The two POM chemical groups most commonly found in emission source exhaust and ambient air are PAHs, which contain carbon and hydrogen only, and the PAH-nitrogen analogs. Information available in the literature on POM compounds generally pertains to these PAH groups. Because of the dominance of PAH information (as opposed to other POM categories) in the literature, many reference sources have inaccurately used the terms POM and PAH interchangeably. The majority of information in this report on POM physical/chemical properties, formation mechanisms, and emissions pertains to PAH compounds.

Polycyclic organic compounds are formed in stationary combustion sources as products of incomplete combustion. The rates of POM formation and emission are dependent on both fuel characteristics and combustion process characteristics. Emissions of POM can originate from POM compounds contained in fuels that are released during combustion or from high temperature transformations of organic compounds in the combustion zone (Shih et al., 1980a; National Academy of Sciences, 1972; National Research Council, 1983).

Two important fuel characteristics affecting POM formation in combustion sources are (1) the carbon to hydrogen ratio and molecular structure of the fuel and (2) the chlorine and bromine content of the fuel (Shih et al., 1980a). In general, the higher the carbon to hydrogen ratio, the greater the probability of POM compound formation. Holding other combustion variables constant, the tendency for hydrocarbons present in a fuel to form POM compounds is as follows.

aromatics > cycloolefins > olefins > paraffins

Based on both carbon to hydrogen ratio and molecular structure considerations, the tendency for the combustion of various fuels to form POM compounds is as follows (Shih et al., 1980a).

coal> lignite > wood > waste oil > residual oil > distillate oil

In the formation of chlorinated and brominated POM compounds during stationary source fuel combustion, the chlorine and bromine content of the fuel plays a major role. Based on the chlorine content of fuels, the tendency to form chlorinated POM compounds during combustion is:

bituminous coal > wood > lignite > residual oil > distillate oil

Similarly, based on the bromine content of fuels, the tendency to form brominated POM compounds during combustion is:

bituminous coal > lignite > residual oil > distillate oil > wood

The primary combustion process characteristics affecting POM compound formation and emissions are (Shih et al., 1980a; Hangebrauck et al., 1964; Barrett et al., 1983):

- combustion zone temperature,
- residence time in the combustion zones,
- turbulence or mixing efficiency between air and fuel,
- air/fuel ratio, and
- fuel feed size.

With adequate residence time and efficient mixing, temperatures in the 800-1000°C (1472-1832°F) range will cause complete destruction of POM compounds such as polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), and polychlorinated biphenyls (PCBs). Concentrations of polyaromatic hydrocarbons (PAHs) also decrease rapidly with increasing temperature (Shih et al., 1980a).

The most important reason for incomplete combustion of fuel, thereby resulting in POM formation, is insufficient mixing between air, fuel, and combustion products. Mixing is a function of the combustion unit's operating practices and fuel firing configuration. Hand- and stoker-fired solid fuel combustion sources generally exhibit very poor air and fuel mixing relative to other types of combustion sources. Liquid fuel units and pulverized solid fuel units provide good air and fuel mixing (Shih et al., 1980a; Hangebrauck et al., 1964; Barrett et al., 1983; Kelley, 1983).

The air/fuel ratio present in combustion environments is important in POM formation because certain quantities of air (i.e., oxygen) are needed to stoichiometrically carry out complete combustion. Air supply is particularly important in systems with poor air and fuel mixing. Combustion environments with a poor air supply will generally have lower combustion temperatures and will not be capable of completely oxidizing all fuel present. Systems experiencing frequent start-up and shut-down will also have poor air/fuel ratios. Unburned hydrocarbons, many as POM compounds, can exist in such systems and eventually be emitted through the source stack. Generally, stoker and hand-fired solid fuel combustion sources have problems with insufficient air supply and tend to generate relatively large quantities of POM as a result (Shih et al., 1980a; Kelley, 1983; Barrett et al., 1983).

In solid and liquid fuel combustion sources, fuel feed size can influence combustion rate and efficiency, therefore, POM compound formation is affected. For liquid fuel oils, a poor initial fuel droplet size distribution is conducive to poor combustion conditions and an enhanced probability of POM formation. In most cases, fuel droplet size distribution is primarily influenced by fuel viscosity. As fuel viscosity increases, the efficiency of atomization decreases and the droplet size distribution shifts to the direction of larger diameters. Therefore, distillate oils are more readily atomized then residual oils and result in finer droplet size distribution. This behavior combined with distillate oil's lower carbon to hydrogen ratio means that residual oil sources inherently have a higher probability of POM formation and emission then distillate oil sources (Shih et al., 1980a; Hangebrauck et al., 1964; Kelley, 1983).

For solid fuels, fuel size affects POM formation by significantly impacting combustion rate. Solid fuel combustion involves a series of repeated steps, each with the potential to form POM compounds. First, the volatile components near the surface of a fuel particle are burned followed by burning of the residual solid structure. As fresh, unreacted solid material is exposed, the process is repeated. Thus, the larger the fuel particle, the greater the number of times this sequence is repeated and the longer the residence time required to complete the combustion process. With succeeding repetitions, the greater the probability of incomplete combustion and POM formation. Again, stoker and hand-fired solid fuel combustion units represent the greatest potential for POM emissions due to fuel size considerations (Shih et al., 1980a).

Polycyclic organic matter can be emitted from fuel combustion sources in both gaseous and particulate phases. The compounds are initially formed as gases, but as the flue gas stream cools, a portion of the POM constituents adsorb to solid fly ash particles present in the stream. The rate of adsorption is dependent on temperature, and on fly ash and POM compounds characteristics. At temperatures above 150°C (302°F), most POM compounds are expected to exist primarily in gaseous form. In several types of fuel combustion systems, it has been shown that POM compounds are preferentially adsorbed to smaller (submicron) fly ash particles because of their larger surface area to mass ratios. These behavioral characteristics of POM emissions are important in designing and assessing POM emission control systems (Shih et al., 1980a; Kelley, 1983; Griest and Guerin, 1979; Sonnichsen, 1983).

EFFECTS OF COMBUSTION SOURCE DESIGN AND CONTROL TECHNOLOGY ON EMISSIONS

Characteristics of the Boiler Population

Boiler Design-

Boiler design influences the rate of trace metal and POM emissions. Types of coal-fired boilers used in the utility, industrial, and commercial/institutional sectors include pulverized coal-fired, cyclone, and stoker units. Pulverized units are characterized by ash removal method as dry bottom or wet bottom. There is little variation in the design of oil-fired units, and almost all are tangentially fired. Table 3-56 shows the prevalence of each boiler type (in terms of 1978 fuel use) in the utility, industrial, and commercial/institutional sectors.

The utility sector is dominated by pulverized dry bottom coal-fired units. In the future, the percentage of these units is expected to increase. Coal-fired pulverized wet bottom and cyclone boilers are no longer sold due to their inability to meet NO_x standards. Stoker boilers, currently accounting for less than one percent of the total, are obsolete due to their inefficiency and are being retired.

In the industrial sector, more natural gas is used relative to coal and oil. Pulverized coal-fired units are the most common type of coal-fired unit; however, stoker units (mainly spreader stokers) also account for a large percentage of total coal use.

The commercial/institutional sector consumes a greater proportion of oil and natural gas relative to coal consumption than the other two sectors. Small underfeed stokers are the predominant type of coal-fired boiler. Some

TABLE 3-56. POPULATION CHARACTERISTICS OF UTILITY, INDUSTRIAL AND COMMERCIAL BOILERS IN TERMS OF BOILER DESIGN AND FUELS, 1978

	Percent of Total Fuel Use (Heat Input) for Each Sector		
Boiler Type	Utility[a]	Industrial[b]	Commercial/ Institutional[c]
Coal-Fired Boilers			
Pulverized Dry Bottom	49.6	7.1	0.4
Pulverized Wet Bottom	7.2	1.7	0.02
Cyclone	7.4	0.4	-
Stoker	0.7	7.1	2.4
Oil-Fired Boilers	21.6	19.6	51.6
Gas-Fired Boilers	13.6	57.4	43.6
Other[d]	-	0.01	0.04
Total fuel consumption by external combustion sources (10^{12} Btu)	16,761	8,236	4,777

[a] Source: Shih et al., 1980b
[b] Source: Suprenant et al., 1980a
[c] Source: Suprenant et al., 1980b
[d] Other includes wood and refuse.

of the larger institutional sources in this sector are pulverized coal-fired boilers and spreader stokers.

Control Status-

All coal-fired utility boilers are equipped with some form of particulate emissions control device. High efficiency electrostatic precipitators (ESPs) are the most common. Data on the distribution of control techniques for coal-fired utility boiler particulate emissions are shown in Table 3-57 (Radian Corporation, 1983). A study of coal-fired utility boilers larger than 100 MW and placed in service since 1950 showed that in 1980 about 92 percent of the generating capacity was controlled with ESPs, 2 percent with fabric filters, 1 percent with scrubbers, and the control status of 5 percent was unknown (Barrett et al., 1983). New units subject to NSPS must control particulate emissions by about 99 percent, so the control status of coal-fired utility boilers is expected to improve over time. More current (1984) data on the control status of utility boilers is contained in the POWER data base maintained by the Utility Data Institute (UDI) in Washington, D.C.

The Utility Data Institute is a private data base management group under contract to the Edison Electric Institute (EEI) to manage their "POWER" data base. The data base contains power plants utilizing coal, oil, and other fuels organized alphabetically by State. Information included for each plant includes about 300 parameters including name, location, latitude and longitude, capacity, fuel type, fuel use, criteria pollutant emissions, control status, and stack parameters. Most of the data are obtained from DOE/EIA Form 767. The utilities send UDI a copy of these forms when they return them to DOE. Other data comes from direct contacts and surveys of utilities.

In 1984, about 17 percent of the utility coal generating capacity was equipped with flue gas desulfurization (FGD) systems. The majority of these were lime or limestone scrubber systems. It is predicted that by 1992, about 31 percent of coal generating capacity will be equipped with FGD systems (Melia et al., 1984).

Oil-fired utility boilers are often uncontrolled; however some are equipped with mechanical precipitators, cyclones, or ESPs (Shih et al.,

TABLE 3-57. BREAKDOWN OF CONTROL TECHNIQUES FOR REDUCING PARTICULATE EMISSIONS FROM COAL-FIRED UTILITY BOILERS

Control Device Type	Number of Boilers With This Control	Percent of Total Generating Capacity Represented
ESP[a]	979	92.6
Wet Scrubber[b]	32	4.2
Baghouse	47	2.1
Mechanical Collector[c]	137	1.1

[a] ESP category also includes units listed as having a combination of control techniques, units using flue gas conditioning to improve ESP performance, and a small number of units for which no control method was listed.

[b] Does not include units with scrubbers for flue gas desulfurization (FGD) unless the scrubber is the only particulate control device.

[c] Includes units which have only mechanical control techniques (cyclones, multicyclones).

Source: Radian Corporation, 1983.

1980b). The POWER data base contains current information on the control status of oil-fired utility boilers.

Coal-fired industrial boilers are less well controlled than utility boilers. Based on a 1976 survey of over 2,500 units, about 14 percent were controlled with ESPs, 47 percent with cyclones, 4 percent with scrubbers, 1 percent with fabric filters, and 33 percent were uncontrolled (Suprenant et al., 1980a). The applicability of these percentages to the entire industrial boiler population is unknown. In general, larger units are more likely to be controlled than smaller units, and pulverized coal and cyclone boilers are more likely to be controlled than stokers (Suprenant et al., 1980a). The NSPS for industrial boilers (>100 million Btu) and small boilers (≤100 million Btu) will result in improved emissions control in the future. Oil-fired industrial boilers are typically uncontrolled.

Commercial and residential boilers and furnaces are typically uncontrolled. However, cyclones are in place at some of the larger commercial/institutional coal-fired boilers (Suprenant et al., 1980b).

Trace Metal and Radionuclide Emissions

Boiler design affects the amount of ash entrained in the flue gas. Since all of the trace metals and radionuclides reviewed, except mercury, are emitted predominantly in particulate form, the amount of fly ash emitted will influence the amount of trace metals emitted. Table 3-58 presents the fraction of coal ash emitted as fly ash for different combinations of boiler firing configurations and coal types (Baig et al., 1981). The fractions for bituminous coal-fired boilers are based on several tests. The values for lignite and anthracite are much less certain. Further testing is necessary to determine if the three types of coals generate different ratios of fly ash to bottom ash when burned in similar boilers.

Boiler configuration may also affect the volatilization/condensation behavior of trace elements, and hence their emission rates. This is especially true for Class 3 elements which show enrichment in the fly ash in some studies and not in others (Baig et al., 1981). Elements may be more likely to be vaporized in large pulverized coal-fired boilers where

TABLE 3-58. COAL ASH DISTRIBUTION BY BOILER TYPE[a]

Furnace Type	Percent Fly Ash/Percent Bottom Ash Bituminous Coal[b]	Lignite Coal[c]	Anthracite Coal[c]
Pulverized dry bottom	80/20	35/65	85/15
Pulverized wet bottom	65/35	--	--
Cyclone	13.5/86.5	30/70	--
Stoker	60/40	35/65	5/95

[a] Source: Baig et al., 1981

[b] Based on several studies of coal ash from large and intermediate size coal-fired boilers.

[c] Based on an analysis of uncontrolled particulate emissions.

combustion is more efficient due to higher temperatures, longer residence times, and efficient mixing of air and fuel; and they may be volatilized to a lesser degree in smaller, less efficient, lower temperature combustion systems. The temperature of the stack gas and fly ash characteristics influence the condensation behavior of volatilized trace metals and their adsorption onto fly ash particles.

The efficiency of control devices in removing trace elements depends on whether the elements are in vapor or particulate form and on the size of the fly ash particles with which the elements are associated. Typical particulate controls on industrial and utility boilers include multicyclones and ESPs. Scrubbers are applied to some utilities for SO_2 (and particulate) control. For elements such as manganese, which tend to show an even distribution on all sizes of particulates, collection efficiency of particulate control devices should be similar to overall particulate control efficiency. However other elements such as arsenic, cadmium, copper and U-238 are enriched in the smaller particulate fractions (<1 um). Mechanical collection devices such as cyclones and multicyclones generally show decreasing collection efficiency as particle size decreases; therefore, the collection efficiency of trace elements concentrated on small particles will be less than overall particulate collection efficiency. Although not as severe as for cyclones, this condition also exists for scrubbers and ESPs. ESPs often show a minimum collection efficiency in the 0.1 to 1 um diameter size range (Ondov et al., 1979a).

Furthermore, ESPs and cyclones will not reduce emissions of elements, such as mercury, emitted in the vapor phase. A portion of the other trace metals, especially the Class 2 elements, may also remain in vapor form in the flue gas, and may thereby escape collection.

Polycyclic Organic Matter Emissions

Polycyclic organic matter emission rates are also influenced by boiler design. As noted previously, POM formation depends on temperature, residence time, efficiency of air and fuel mixing, air/fuel ratio, and fuel feed size. Based on these criteria, pulverized dry bottom and wet bottom coal-fired units would have the lowest POM emission factors of any coal-fired units. These units are generally large, temperature of the combustion zone is high [around 1,650°C (3,000°F)], residence time in the combustion zone is relatively long (0.5 sec), air/fuel ratios are constant and adequate for efficient combustion, and the coal feed is pulverized into small particles. Cyclone-fired boilers would have the next lowest POM emission rates. Stokers would have higher emission rates, with overfeed and underfeed stokers having slightly higher emission rates than spreader stokers. Stoker units are usually smaller, temperatures in the combustion zone are lower due to the 30 to 60 percent excess air present, mixing between air and fuel is less efficient, the on-off cycle results in fluctuations in the air/fuel ratio, and fuel feed size is larger. These factors lead to increased POM formation. Hand stoked units would have the highest emission factors of all coal-fired units (Shih et al., 1980a; Barrett et al., 1983).

Oil-fired units have less of a tendency to form POM than coal-fired units due to fuel characteristics. Based on fuel characteristics, residual oil fired units are more likely to form POM than distillate oil fired units. Based on boiler design characteristics, large oil-fired utility boilers would have the lowest POM emission rates, followed by industrial boilers. Based on design, home heating units would have higher POM emission rates; however, these are usually fired with distillate oil which would tend to reduce emissions (Shih et al., 1980a).

Polycyclic organic matter is emitted in both vapor and particulate phases, with the vapor phase generally predominating, and the particulate phase showing small particle enrichment. Particulate POM, particularly fine particles, would be controlled most effectively by baghouses or ESPs. No control of gaseous POMs would be achieved by baghouse and ESP systems. Wet scrubbers could potentially be effective for controlling particulate and gaseous POM. Scrubbers would condense the POM compounds existing as vapors and collect them as the gas stream is saturated in the scrubber. Multicyclones would be the poorest control system for POM emissions because they are ineffective on fine particles and would have no control effect on gaseous POM (Kelley, 1983).

Wet FGD/ESP systems, while providing for the control of POM condensed on particulate matter at the entrance to the ESP, have been shown to be poor at controlling vapor phase POM. Tests examining benzo(a)pyrene showed that condensation of the vapor phase POM compound would occur in the scrubber, but significant collection of POM particles remaining in the gas flow through the scrubber was not achieved (Kelley, 1983).

SECTION 4

TOXIC AIR POLLUTANT EMISSION FACTORS FOR COAL AND OIL COMBUSTION

This section contains emission factors for selected toxic air pollutants from coal and oil combustion. Factors are presented for arsenic, beryllium, cadmium, chromium, copper, manganese, mercury, nickel, lead, formaldehyde, POM, and selected radionuclides (uranium-238, thorium-232).

EMISSION FACTORS FOR OIL-FIRED COMBUSTION SOURCES

The literature was reviewed for measured and calculated oil emission factors. A summary of emission factors for the nine trace metals, POM, and formaldehyde emitted from the combustion of residual and distillate oil are presented and discussed below. No data were identified for radionuclide emissions from oil combustion.

The summarized emission factors should not be construed to represent a fully characterized or representative emission rate for the given combustion source situation. Extensive data quality assurance procedures, necessary to reasonably characterize a data set as representative of a particular source, were not performed in this study because of time and budgetary constraints. Instead, the summarized factors are simply straightforward calculations of emission factor averages and ranges based on data presented in the literature. The summarized factors are not to be considered as suggested emission factor values for use in other activities such as regulatory development or specification of acceptable ambient concentrations.

Summary of Emission Factors

A summary of toxic pollutant emission factors for residual and distillate oil combustion are presented in Table 4-1. These are uncontrolled emission factors that could be used in efforts such as emission

TABLE 4-1. SUMMARY OF TOXIC POLLUTANT EMISSION FACTORS FOR OIL COMBUSTION[a]

Pollutant	Emission Factor ($lb/10^{12}$ Btu) Residual Oil	 Distillate Oil
Arsenic	19	4.2
Beryllium	4.2	2.5
Cadmium	15.7	10.5
Chromium	21	48
Copper	280	280
Lead	28[c]	8.9[d]
Mercury	3.2	3.0
Manganese	26	14
Nickel	1260	170
POM	8.4[b]	22.5
Formaldehyde	405[e]	405[e]

[a] All emission factors are uncontrolled, and are applicable to oil-fired boilers and furnaces in all combustion sectors unless otherwise noted.

[b] This value was calculated using all available residual oil data given in Table 4-35. If the upper end of the range of available data is excluded when calculating an average value (which could be used in this table), the average factor for POM from residual oil combustion becomes 4.1 $lb/10^{12}$ BTU.

[c] Applicable to utility boilers only.

[d] Applicable to industrial, commercial, and residential boilers.

[e] The formaldehyde factors are based on very limited and relatively old data. Consult Table 4-37 and accompanying discussion for more detailed information.

inventory development. They are applicable to all types of oil-fired boilers in all four combustion sectors (utility, industrial, commercial/institutional, and residential).

Derivation of Summary Trace Metal Emission Factors-

The summarized emission factors for eight of the nine trace metals studied were calculated from the typical level of these metals in residual and distillate oil assuming the entire mass of the trace metals entering the boiler in the oil feed is emitted in the flue gas. Typical values for the trace element content of residual and distillate oils presented in Section 3 were used in the calculations. These were average values based on a review of several previous studies of the trace element composition of oil. Typical trace metal concentrations in the oil feed (expressed in ppm) were converted to emission factors (lb trace metal emitted per 10^{12} Btu of oil burned) assuming heating values of 150,000 Btu/gal for residual oil and 141,000 Btu/gal for distillate oil, and densities of 944 g/l (7.88 lb/gal) for residual oil and 845 g/l (7.05 lb/gal) for distillate oil. The heating values are documented in Appendix B.

Since oil combustion generates no bottom ash, the assumption that 100 percent of the trace metals entering the boiler in the oil feed are emitted in the flue gas is reasonable. The calculated uncontrolled emission factors based on this assumption would be independent of boiler design and combustion sector.

Limited emission factor data for lead emissions from oil combustion are presented here. The consideration of lead as a trace pollutant from coal and oil combustion was added to this project by EPA late in the data analyses process. For this reason, the treatment of lead, including the availability of emission factor data, is very abbreviated compared to the other trace pollutants in the document. Only a limited number of the references listed in the report bibliography in Section 6 were evaluated for lead data.

The general agreement between measured and calculated emission factors from several references lends some confidence to the summarized values. However, they should be considered in light of the high variability of trace elements in oil. Furthermore, the data base on distillate oil was much less complete than the data base on residual oil and coal. For some metals, there were only two or three available studies reporting their occurrence in distillate oil. The representativeness of the distillate oil emission factors is, therefore, somewhat uncertain.

Another data gap is the effects of particulate control technologies on trace metal emissions from oil-fired boilers. Many trace metals are enriched in the small particle fractions of the fly ash from coal combustion sources. However, oil fly ash has different characteristics, and whether the volatilization/condensation theories predicting small particle enrichment are applicable to oil combustion sources is uncertain. There is a lack of literature on the form of trace emissions from oil combustion (vapor or particulate) and on the association of trace elements with various size fractions of the oil fly ash. Without this information, the efficiency of particulate control devices at removing trace metal emissions cannot be calculated. Almost all of the calculated and measured emission factors reported in previous studies are uncontrolled.

Derivation of POM and Formaldehyde Emission Factors-

A qualitative discussion of theories of POM and formaldehyde formation and behavior during combustion is presented in Section 3. No methods for calculating POM and formaldehyde emission factors were found in the literature. The emission factors presented in Table 4-1 are average values derived from test data contained in the literature.

More test data are available for POM emission factors from residual oil than from distillate oil. Reported POM emission factors for both types of oil vary over two orders of magnitude. The data show no clear pattern as to whether boiler type, boiler size, combustion sector, or oil grade influence POM emissions. Part of the observed variation may be due to variations in sampling and analytical methodology between studies.

Only four measured formaldehyde emission factors were available in the literature. While these are in fairly close agreement, the scarcity of data make the representativeness of the summarized emission factor highly uncertain. There are not enough data to derive separate formaldehyde emission factors for residual versus distillate oil.

The effect of particulate control technologies on POM and formaldehyde emissions is another area lacking data. There are few measurements of POM in controlled emission streams, and little data on the distribution of POM and formaldehyde in the vapor versus particulate phases. Theoretically, a large portion of POM and formaldehyde should be present in vapor form and would therefore escape collection; however, very limited test data for residual oil-fired sources appears to indicate lower POM emission factors for controlled versus uncontrolled boilers.

Arsenic Emission Factors

Based on a typical residual oil arsenic content of 0.36 ppm, the summarized uncontrolled arsenic emission factor for residual oil combustion is 19 lb/10^{12} Btu. This is in the middle range of values calculated in five previous studies, which range from less than 0.5 to 42 lb/10^{12} Btu (see Table 4-2). Eight measured arsenic emission factors from the literature are shown in Table 4-3. Uncontrolled emission factors reported by two authors range from 4.2 to 37 lb/10^{12} Btu, and are in good agreement with the recommended value of 19 lb/10^{12} Btu. Since levels in fuels were often below the detection limit, it is not possible to calculate mass balance closure for the test runs. Leavitt et al. (1980) reports higher emission factors, despite the presence of control devices. The reason for this is unknown.

The summarized distillate oil arsenic emission factor is 4.2 lb/10^{12} Btu based on a typical level of 0.085 ppm in distillate oil. This is in good agreement with previously calculated factors of 3.0 and 8.1 lb/10^{12} Btu from two studies summarized in Table 4-4. Only four measured values are reported in the literature, ranging from 1.5 to 3.5 lb/10^{12} Btu (see Table 4-5).

Beryllium Emission Factors

The summarized uncontrolled beryllium emission factor for residual oil is 4.2 lb/10^{12} Btu. This is in general agreement with previously calculated values shown in Table 4-6 which range from 0.05 to 5.57 lb/10^{12} Btu. There is some uncertainty regarding the calculated values reported in the

TABLE 4-2. CALCULATED UNCONTROLLED ARSENIC EMISSION FACTORS FOR RESIDUAL OIL-FIRED BOILERS[a]

	Summary Emission Factor[b,c]	Previous Studies				
		Tyndall et al., 1978	Shih et al., 1980b	Suprenant et al., 1980a	Suprenant et al., 1980b	Leavitt et al., 1980b
Emission Factor ($lb/10^{12}$ Btu)	19	42	28	2.8	21.1	0.5
Concentration in Fuel (ppm)	0.36	0.8	0.51	---	.087-0.4	0.01

[a] Calculated assuming all arsenic present in the oil feed is emitted through the stack.

[b] Based on typical level of arsenic in residual oil derived in Section 3. Emission factor assumes all arsenic present in oil feed is emitted through the stack. A density of 944 g/l and a heating value of 150,000 Btu/gal are assumed.

[c] Calculated arsenic emission factors ($lb/10^{12}$ Btu) for controlled residual oil fired boilers are: multiclone, 9.31; ESP, 2.28; scrubber, 1.90. See text for discussion.

TABLE 4-3. MEASURED ARSENIC EMISSION FACTORS FOR RESIDUAL OIL-FIRED BOILERS

Emission Factor (lb/10^{12} Btu)	Fuel Characteristics Type	Fuel Characteristics (Arsenic Content, ppm)	Control Status	Sectors[a]	Boiler Type	Reference
7.0[b]	1:1 Residual/ Crude Oil	(<1.0)	Uncontrolled	U	Wall-fired	Sawyer and Higginbotham, 1981b
27[c]	1:1 Residual/ Crude Oil	(<2.0)	Uncontrolled	U	Wall-fired	Sawyer and Higginbotham, 1981b
6.3[d]	1:1 Residual/ Crude Oil	(<2.0)	Uncontrolled	U	Wall-fired	Sawyer and Higginbotham, 1981b
4.2[e]	#6 Oil	(<2.0)	Uncontrolled	I	Water tube	Carter et al., 1978
34[f]	#6 Oil	(<2.0)	Uncontrolled	I	Water tube	Carter et al., 1978
37[f]	#6 Oil	(<2.0)	Uncontrolled	I	Water tube	Carter et al., 1978
114[g]	#6 Oil	(<2.0)	Multiclone (tested at scrubber inlet)	I	Integral Coal/ Oil Furnace	Leavitt et al., 1978b; Fischer et al., 1979
22[h]	#6 Oil	(2.0)	Multiclone/ Scrubber	I	Integral Coal/ Oil Furnace	Leavitt et al., 1978b; Fischer et al., 1979

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

[b] Tested under baseline (design) operating conditions.

[c] Low-NO_x operating conditions - flue gas is recirculated, top row of burners admit air only while lower burners admit fuel at greater than baseline rates.

[d] Low-NO_x operating conditions - flue gas is recirculated, all burners in service.

[e] Tested under baseline (design) conditions. Arsenic determined by atomic absorption.

[f] Tested under low-NO_x operating conditions - reduced excess air and maximum flue gas recirculation. Arsenic determined by atomic absorption.

[g] Tested at scrubber inlet of the same boiler as in footnote h.

[h] Tested at scrubber outlet.

TABLE 4-4. CALCULATED UNCONTROLLED ARSENIC EMISSION FACTORS FOR DISTILLATE OIL-FIRED BOILERS[a]

	Summary Emission Factor[b,c]	Previous Studies	
		Suprenant et al., 1980b	Suprenant et al., 1980a
Emission Factor ($lb/10^{12}$ Btu)	4.2	3.0[d]	8.1
Concentration in Fuel (ppm)	0.085	0.1-0.21[d]	---

[a] Calculated assuming all arsenic present in oil feed is emitted through the stack.

[b] Calculated from typical level of arsenic in distillate oil derived in Section 3. Emission factor assumes all arsenic present in oil feed is emitted through the stack. A density of 7.05 lb/gal and heating value of 141,000 Btu/gal are assumed.

[c] Calculated arsenic emission factors ($lb/10^{12}$ Btu) for controlled distillate oil-fired boilers are: multiclone, 2.06; ESP, 0.50; scrubber, 0.42. See text for discussion.

[d] There is an apparent discrepancy between the calculated emission factor and the values measured for arsenic in the fuel as reported in this reference. The reference states the assumption that all arsenic measured in the oil feed is emitted through the stack, but the numbers presented do not agree with this statement. This discrepancy could not be resolved from the information given in the reference.

TABLE 4-5. MEASURED ARSENIC EMISSION FACTORS FOR DISTILLATE OIL-FIRED BOILERS

Emission Factor (lb/10^{12} Btu)	Fuel Characteristics		Control Status	Sector[a]	Boiler Type	Reference
	Type	(Arsenic Content, ppm)				
3.5[b]	Distillate	---	Uncontrolled	R	Conventional High Pressure	Suprenant et al., 1979
2.5[c]	Distillate	(<0.9)	Uncontrolled	R	Blueray Low NO_x	Castaldini et al., 1981b
2.0[d]	Distillate	(<0.9)	Uncontrolled	R	Blueray Low NO_x	Castaldini et al., 1981b
1.5	Distillate	(0.019)	Uncontrolled	R	Hot Water Condensing Heating System	Castaldini et al., 1982

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

[b] Average of eight tests run on seven units.

[c] Unit operating in a cycling mode, 10 minutes on, 10 minutes off.

[d] Unit operating continuously.

TABLE 4-6. CALCULATED UNCONTROLLED BERYLLIUM EMISSION FACTORS FOR RESIDUAL OIL-FIRED BOILERS[a]

	Summary Emission Factor[b,c]	Previous Studies					
		Tyndall et al, 1978	Shih et al, 1980b	Suprenant et al, 1980a	Suprenant et al, 1980b	Leavitt et al, 1980b	Anderson, 1973
Emission Factor ($lb/10^{12}$ Btu)	4.2	4.2	5.57	0.05	0.15[d]	0.5	5.3
Concentration in Fuel (ppm)	0.08	0.08	0.10	---	0.0042-0.038[d]	0.01	0.1

[a] Calculated assuming all beryllium present in the oil feed is emitted through the stack.

[b] Based on typical level of beryllium in residual oil derived in Section 3. Emission factor assumes all beryllium present in the oil feed is emitted through the stack. A density of 944 g/l and a heating value of 150,000 Btu/gal are assumed.

[c] Calculated beryllium emission factors ($lb/10^{12}$ Btu) for controlled residual oil-fire boilers are: multiclone, 2.65; ESP, 0.59; scrubber, 0.25. See text for discussion.

[d] There is an apparent discrepancy between the calculated emission factor and the values measured for beryllium in the fuel as reported in the reference. The reference states the assumption that all beryllium measured in the oil feed is emitted through the stack, but the numbers presented do not agree with this statement. This discrepancy could not be resolved from the information given in the reference.

Suprenant et al. (1980a, 1980b) studies. The reference stated that emission factors were calculated assuming all beryllium present in the oil feed is emitted; however, the numbers presented for beryllium levels in oil and corresponding emission factors do not agree with this statement (see Table 4-6). The calculated beryllium factors reported by Tyndall et al. (1978), Shih et al. (1980b), and Anderson (1973) are in closer agreement with the summarized factor than are the values reported by Suprenant et al. (1980a, 1980b).

Measured beryllium emission factors for residual oil combustion vary over three orders of magnitude, from 0.14 to 250 lb/10^{12} Btu, as shown in Table 4-7. The causes of this variation are uncertain. Since beryllium contents of many of the fuels were below the detection limit, mass balance closure for the test runs cannot be calculated.

The summarized beryllium emission factor for distillate oil is 2.5 lb/10^{12} Btu, as shown in Table 4-8. This is higher than that reported in previous studies by Suprenant et al. (1980a; 1980b); but as explained in the preceding paragraph and in Table 4-8, there is a discrepancy between the values Suprenant et al. (1980b) reported for beryllium content of oil and the corresponding calculated emission factors reported. The values are not consistent with the assumptions stated in that reference about the calculation procedures. Three tests of beryllium emissions from distillate oil-fired sources are shown in Table 4-9. Measured beryllium emission factors range from 0.52 to 1.2 lb/10^{12} Btu, which are slightly below the summarized value of 2.5 lb/10^{12} Btu, but much higher than the values previously calculated by Suprenant et al. (1980a, 1980b).

Cadmium Emission Factors

The summary uncontrolled cadmium emission factor for residual oil combustion sources is 15.7 lb/10^{12} Btu. Table 4-10 compares this factor with values calculated in six previous studies. It is in general agreement with values for domestic residual oil combustion calculated by Shih et al. (1980b) and Anderson (1973). The validity of emission factors calculated in Suprenant et al. (1980b) is uncertain because the level of cadmium in oil and

TABLE 4-7. MEASURED BERYLLIUM EMISSION FACTORS FOR RESIDUAL OIL-FIRED BOILERS

Emission Factor ($lb/10^{12}$ Btu)	Fuel Characteristics		Control Status	Sectors[a]	Boiler Type	Reference
	Type	(Be Content, ppm)				
1.3	#6 Oil	(0.024)	ESP	U	NR	Anderson, 1973
0.27[b]	1:1 Residual Crude	(<1.0)	Uncontrolled	U	Wall-Fired	Sawyer and Higginbotham, 1981b
250[c]	1:1 Residual Crude	(<2.0)	Uncontrolled	U	Wall-Fired	Sawyer and Higginbotham, 1981b
0.14[d]	1:1 Residual/ Crude	(<2.0)	Uncontrolled	U	Wall-Fired	Sawyer and Higginbotham, 1981b
4.0[e]	#6 Oil	(<3.0)	Uncontrolled	I	Watertube Boiler	Carter et al., 1978
5.3[f]	#6 Oil	(<3.0)	Uncontrolled	I	Watertube Boiler	Carter et al., 1978
3.7[f]	#6 Oil	(<3.0)	Uncontrolled	I	Watertube Boiler	Carter et al., 1978
0.7[g]	#6 Oil	(<0.05)	Multiclone (tested at Scrubber Inlet)	I	Integral Coal/ Oil Furnace	Leavitt et al., 1978b; Fischer et al., 1979
0.7[g]	#6 Oil	(<0.05)	Multiclone/FGD Scrubber	I	Integral Coal/ Oil Furnace	Leavitt et al., 1978b; Fischer et al., 1979

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residual.

[b] Tested under baseline (design) operating conditions.

[c] Tested under low-NO_x operating conditions - flue gas is recirculated, top row of burners admit air only while lower burners admit fuel at greater than baseline.

[d] Tested under low-NO_x operating conditions - flue gas is recirculated, all burners in service.

[e] Tested under baseline (design) conditions.

[f] Tested under low-NO_x operating conditions - reduced excess air and maximum flue gas recirculation. Beryllium determined by atomic absorption.

[g] Tested at scrubber inlet of the same boiler as in footnote h.

[h] Tested at scrubber outlet.

TABLE 4-8. CALCULATED UNCONTROLLED BERYLLIUM EMISSION FACTORS FOR DISTILLATE OIL-FIRED BOILERS[a]

	Summary Emission Factor[b,c]	Previous Studies: Suprenant et al., 1980b	Previous Studies: Suprenant et al., 1980a
Emission Factor ($lb/10^{12}$ Btu)	2.5	0.09[d]	0.05
Concentration in Fuel (ppm)	0.05	0.0076[d]	---

[a] Calculated assuming all beryllium present in oil feed is emitted through the stack.

[b] Calculated from typical level of beryllium in distillate oil derived in Section 3. Emission factor assumes all beryllium present in oil feed is emitted through the stack. A density of 7.05 lb/gal and heating value of 141,000 Btu/gal are assumed.

[c] Calculated beryllium emission factors ($lb/10^{12}$ Btu) for distillate oil-fired boilers are: multiclone, 1.58; ESP, 0.35; scrubber, 0.15. See text for discussion.

[d] There is a discrepancy between the calculated emission factor and the values measured for beryllium in the fuel as reported in this reference. The reference states the assumption that all beryllium measured in the oil feed is emitted through the stack, but the numbers presented do not agree with this statement. This discrepancy could not be resolved from the information given in the reference.

TABLE 4-9. MEASURED BERYLLIUM EMISSION FACTORS FOR DISTILLATE OIL-FIRED BOILERS

Emission Factor (lb/10^{12} Btu)	Fuel Characteristics		Control			
	Type	(Beryllium Content, ppm)	Status	Sectors[a]	Boiler Type	Reference
0.64	Distillate	(0.1)	Uncontrolled	R	Blueray Low NO_x	Castaldini *et al.*, 1981b
0.52[b]	Distillate	(0.1)	Uncontrolled	R	Blueray Low NO_x	Castaldini *et al.*, 1981b
1.2[c]	Distillate	(0.19)	Uncontrolled	R	Hot Water Condensing Heating Systems	Castaldini *et al.*, 1982

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

[b] Unit operating in a cycling mode, 10 minutes on, 10 minutes off.

[c] Unit operating continuously.

TABLE 4-10. CALCULATED UNCONTROLLED CADMIUM EMISSION FACTORS FOR RESIDUAL OIL-FIRED BOILERS[a]

	Summary Emission Factor[b,e]	Previous Studies					
		Tyndall et al, 1978	Shih et al 1980b	Suprenant et al 1980a	Suprenant et al, 1980b	Anderson, 1973	Anderson, 1973
Emission Factor (lb/10^{12} Btu)	15.7	121	16	1.5	0.46[c]	130-270	20-27
Concentration in Fuel (ppm)	0.3	2.27	0.30	---	0.02-0.94[c]	3.0-5.0[d]	0.4-0.5

[a] Calculated assuming all cadmium present in oil feed is emitted through the stack.

[b] Based on typical level of cadmium in residual oil derived in Section 3. Emission factor assumes all cadmium present in oil feed is emitted through the stack. A density of 944 g/l and a heating value of 150,000 Btu/gal are assumed.

[c] There is an apparent discrepancy between the calculated emission factor and the values measured for cadmium in the oil as reported in this reference. The reference states the assumption that all cadmium measured in the fuel is emitted through the stack, but the numbers presented do not agree with this statement. This discrepancy could not be resolved from the information given in the reference.

[d] Number 6 oil from the Virgin Islands, Trinidad, and Curacao.

[e] Calculated cadmium emission factors (lb/10^{12} Btu) for controlled residual oil-fire boilers are: multiclone, 46.86; ESP, 9.90; scrubber, 3.96. See text for discussion.

corresponding calculated emission factors reported in this study are inconsistent with the calculation procedures described in the reference.

Measured cadmium emission factors from previous studies, shown in Table 4-11, range from 0.048 to 212 lb/10^{12} Btu. Values reported by Leavitt et al. (1978b) are higher than values reported in the other studies despite the presence of particulate control devices. The causes of the large variation in measured cadmium emission factors are unknown.

The summary cadmium emission factor for distillate oil combustion is 10.5 lb/10^{12} Btu. This value is similar to previously calculated factors shown in Table 4-12 and to three measured emission factors of 4.9 to 25.6 lb/10^{12} Btu shown in Table 4-13. Cadmium was not detected in a fourth test. As described in Table 4-12 and in the preceding paragraph, there is some question as to the method of derivation and validity of the previously calculated emission factors reported by Suprenant et al. (1980b).

Chromium Emission Factors

Based on a typical chromium level of 0.4 ppm in residual oil, the summarized chromium emission factor is 21 lb/10^{12} Btu. This is in general agreement with values calculated in four previous studies ranging from 5 to 69.7 lb/10^{12} Btu (see Table 4-14). The fifth study, by Suprenant et al. (1980b), reported chromium levels in oil of 0.2 to 0.5 ppm, which are similar to the summary value of 0.4 ppm; but the same study reported a calculated emission factor of 116 lb/10^{12} Btu. This is inconsistent, since it would mean that more chromium is emitted from the boiler than is contained in the oil feed.

Measured chromium emission factors shown in Table 4-15 are generally higher than calculated emission factors. Several references reporting emissions tests of coal-fired boilers noted that corrosion of the sampling train components was suspected to occur causing chromium measurements to be too high (Baig et al., 1981). Since sampling systems used at oil-fired sources are similar, contamination due to corrosion of the sampling train components may partially account for the measured values being higher than the calculated chromium emission factors. Mass balances for some of the studies indicate more chromium being emitted than is contained in the oil

TABLE 4-11. MEASURED CADMIUM EMISSION FACTORS FOR RESIDUAL OIL-FIRED BOILERS

Emission Factor ($lb/10^{12}$ Btu)	Fuel Characteristics		Control Status	Sector[a]	Boiler Type	Reference
	Type	(Cadmium Content, ppm)				
33[b]	1:1 Residual/ Crude	(0.5)	Uncontrolled	U	Wall-Fired	Sawyer and Higginbotham, 1981b
8.2[c]	1:1 Residual/ Crude	(0.7)	Uncontrolled	U	Wall-Fired	Sawyer and Higginbotham, 1981b
0.048[d]	1:1 Residual/ Crude	(0.7)	Uncontrolled	U	Wall-Fired	Sawyer and Higginbotham, 1981b
8.6[e]	#6 Oil	(3.0)	Uncontrolled	I	Watertube	Carter et al., 1978
3.0[f]	# 6 Oil	(3.0)	Uncontrolled	I	Watertube	Carter et al., 1978
0.69[f]	#6 Oil	(3.0)	Uncontrolled	I	Watertube	Carter et al., 1978
212[g]	# 6 Oil	(3.5)	Multiclone	I	Integral Coal/ Oil Furnace	Leavitt et al., 1978b; Fischer et al., 1979
49[h]	#6 Oil	(3.5)	Multiclone/ Scrubber	I	Integral Coal/ Oil Furnace	Leavitt et al., 1978b; Fischer et al., 1979

---

[a] U - Utility, I - Industrial, C - Commercial/Industrial, R - Residential.

[b] Tested under baseline (design) operating conditions.

[c] Tested under low-NO_x operating conditions - flue gas is recirculated, top row of burners admit air only while lower burners admit fuel at greater than baseline rates.

[d] Tested under low-NO_x operating conditions - flue gas recirculated, all burners in service.

[e] Tested under baseline (design) operating conditions. Beryllium determined by atomic absorption.

[f] Tested under low-NO_x operating conditions - reduced excess air and maximum flue gas recirculation. Sample analyzed by atomic absorption.

[g] Tested at scrubber inlet of the same boiler as in footnote h.

[h] Tested at scrubber outlet.

TABLE 4-12. CALCULATED UNCONTROLLED CADMIUM EMISSION FACTORS FOR DISTILLATE OIL-FIRED BOILERS[a]

	Summary Emission Factor[b,c]	Previous Studies	
		Suprenant et al., 1980b	Suprenant et al., 1980a
Emission Factor ($lb/10^{12}$ Btu)	10.5	5.8[d]	3.0
Concentration in Fuel (ppm)	0.21	0.95[d]	---

[a] Calculated assuming all cadmium present in oil feed is emitted through the stack.

[b] Calculated from typical level of cadmium in distillate oil derived in Section 3. Emission factor assumes all cadmium present in oil feed is emitted through the stack. A density of 7.05 lb/gal and heating value of 141,000 Btu/gal are assumed.

[c] Calculated cadmium emission factors ($lb/10^{12}$ Btu) for controlled distillate oil-fired boilers are: multiclone, 7.45; ESP, 1.58; scrubber, 0.63. See text for discussion.

[d] There is an apparent discrepancy between the calculated emission factor and the values measured for cadmium in the fuel as reportrd in this reference. The reference states the assumption that all arsenic measured in the oil feed is emitted through the stack, but the numbers presented do not agree with this statement. This discrepancy could not be resolved from the information given in the reference.

TABLE 4-13. MEASURED CADMIUM EMISSION FACTORS FOR DISTILLATE OIL-FIRED BOILERS

Emission Factor (lb/10^{12} Btu)	Fuel Characteristics Type	Fuel Characteristics (Cadmium Content, ppm)	Control Status	Sector[a]	Boiler Type	Reference
25.6[b]	Distillate	---	Uncontrolled	R	Conventional High Pressure	Suprenant *et al.*, 1979
4.9[c]	Distillate	(0.10)	Uncontrolled	R	Blueray Low NO_x	Castaldini *et al.*, 1981b
7.5[d]	Distillate	(0.10)	Uncontrolled	R	Blueray Low NO_x	Castaldini *et al.*, 1981b
ND[e]	Distillate	(0.19)	Uncontrolled	R	Hot Water Condensing Heating System	Castaldini *et al.*, 1982

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

[b] Average of eight tests run on seven units.

[c] Unit operating in a cycling mode, 10 minutes on, 10 minutes off.

[d] Unit operating continuously.

[e] ND = not detectable.

TABLE 4-14. CALCULATED UNCONTROLLED CHROMIUM EMISSIONS FROM RESIDUAL OIL-FIRED BOILERS[a]

	Summary	Previous Studies				
	Emission Factor[b,c]	Tyndall et al, 1978	Suprenant et al, 1980b	Shih et al, 1980b	Suprenant et al, 1980a	Leavitt et al, 1980b
Emission Factor (lb/10^{12} Btu)	21 (0.15)[d]	69.7	116[e]	48.7	68	5
Concentration in Fuel (ppm)	0.40	1.3	0.2-0.5[e]	0.90	---	0.09

[a] Calculated assuming all chromium in oil feed is emitted through the stack.

[b] Based on typical level of chromium in residual oil derived in Section 3. Emission factor assumes all chromium present in oil feed is emitted through the stack. A density of 944 g/l and a heating value of 150,000 Btu/gal are assumed.

[c] Calculated chromium (total) emission factors (lb/10^{12} Btu) for controlled residual oil-fired boilers are: multiclone, 12.18; ESP, 6.09; scrubbers, 1.68. The calculated hexavalent chromium emission factors (lb/10^{12} Btu) for controlled residual oil-fired boilers are: multiclone, 0.04; ESP, 0.02; scrubber, 0.01. See text for discussion.

[d] The value in parentheses is for hexavalent chromium (Cr^{+6}). It was derived by applying the ratio of hexavalent chromium to total chromium emissions (obtained from tests of a coal-fired boiler) to an existing emission factor for utility boilers burning residual oil.

[e] There is an apparent discrepancy between the calculated emission factor and the values measured for chromium in the fuel as reported in this reference. The reference states the assumption that all arsenic measured in the oil feed is emitted through the stack, but the numbers presented do not agree with this statement. This discrepancy could not be resolved from the information given in the reference.

TABLE 4-15. MEASURED CHROMIUM EMISSION FACTORS FOR RESIDUAL OIL-FIRED BOILERS

Emission Factor (lb/10^{12} Btu)	Fuel Characteristics		Control Status	Sector[a]	Boiler Type	Reference
	Type	(Chromium Content, ppm)				
22.6	#6 Oil	---	Uncontrolled	C	Scotch with Rotary Burner	Levy et al., 1971
4.6	#5 Oil	---	Uncontrolled	C	Scotch with Air Atomizing Burner	Levy et al., 1971
2.0	#4 Oil	---	Uncontrolled	C	Scotch with Air Atomizing Burner	Levy et al., 1971
93[c]	1:1 Residual/ Crude Oil	(5.0)	Uncontrolled	U	Wall-fired	Sawyer and Higginbotham, 1981b
80[d]	1:1 Residual/ Crude Oil	(3.0)	Uncontrolled	U	Wall-fired	Sawyer and Higginbotham, 1981b
120[e]	1:1 Residual/ Crude Oil	(4.0)	Uncontrolled	U	Wall-fired	Sawyer and Higginbotham, 1981b
500[c]	#6 Oil	(<5.0)	Uncontrolled	I	Watertube	Carter et al., 1978
560[f]	#6 Oil	(<5.0)	Uncontrolled	I	Watertube	Carter et al., 1978
330[f]	#6 Oil	(<5.0)	Uncontrolled	I	Watertube	Carter et al., 1978

TABLE 4-15. MEASURED CHROMIUM EMISSION FACTORS FOR RESIDUAL OIL-FIRED BOILERS (Continued)

Emission Factor (lb/10^{12} Btu)	Fuel Characteristics Type	Fuel Characteristics (Chromium Content, ppm)	Control Status	Sector[a]	Boiler Type	Reference
128[g]	#6 Oil	(2.2)	Multiclone (tested at scrubber inlet)	I	Integral Coal/ Oil Burner	Leavitt et al., 1978b; Fischer et al., 1979
13[h]	#6 Oil	(2.2)	Multiclone/ Scrubber	I	Integral Coal/ Oil Burner	Leavitt et al., 1978b; Fischer et al, 1979

---

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

[b] Calculations assume 146,000 Btu/gal for #4 oil; 148,000 Btu/gal for #5 oil; and 150,000 Btu/gal for #6 oil.

[c] Operating under design (baseline) conditions.

[d] Operating under high level of NO_x control - flue gas is recirculated, top row of burners admit air only (no fuel), lower burner admit fuel at greater than baseline rates.

[e] Flue gas recirculation, all burners in service.

[f] Unit operating under low-NO_x conditions - reduced excess air and maximum flue gas recirculation. Sample analyzed by atomic absorption.

[g] Tested at scrubber inlet of the same boiler in footnote h.

[h] Tested at scrubber outlet.

feed. Another factor is that the chromium content of oil used at some of the tested facilities (see Table 4-15) is higher than the typical chromium content of residual oil (0.4 ppm) derived in Section 3.

The summarized chromium emission factor for distillate oil is 47.5 lb/10^{12} Btu. This is based on an assumed chromium content of 0.95 ppm for distillate oil. The summary value is slightly lower than values calculated in two previous studies shown in Table 4-16, (56.0 and 83.7 lb/10^{12} Btu). Measured chromium emission factors from six tests summarized in Table 4-17 range from 2.3 to 370 lb/10^{12} Btu, with five of the six tests reporting emission factors below 67.4 lb/10^{12} Btu. Thus, the measured values generally support the calculated emission factor of 47.5 lb/10^{12} Btu.

Emission factors for hexavalent chromium (Cr^{+6}) for distillate and residual oil combustion are given in Tables 4-14 and 4-16. The factors were derived by applying a ratio of hexavalent chromium to total chromium emissions to existing emission factors for oil combustion. The ratio was obtained through testing a coal-fired spreader stoker boiler and analyzing emissions for both total chromium and hexavalent chromium. In the data source for these emission factors, no distinction was made concerning the types of oil burned. For this report, it was assumed that utility boilers burned residual oil and other boilers burn distillate oil. All emission factors are assumed to be for uncontrolled sources.

Copper Emission Factors

The summarized copper emission factor for residual oil combustion is 278 lb/10^{12} Btu. This is in the middle range of values calculated in previous studies. As shown in Table 4-18, previously calculated values range from 5 to 812 lb/10^{12} Btu depending on the assumed copper content of oil. The measured copper emission factors listed in Table 4-19 vary over a similar range, from 4.6 to 1,100 lb/10^{12} Btu, and are in general agreement with the calculated values. The copper content of the fuels where tests were performed do not correlate directly with measured emission rates. In some cases, mass balances do not exhibit good closure.

TABLE 4-16. CALCULATED UNCONTROLLED CHROMIUM EMISSION FACTORS FOR DISTILLATE OIL-FIRED BOILERS[a]

	Summary Emission Factor[b,c]	Previous Studies	
		Suprenant et al., 1980b	Suprenant et al., 1980a
Emission Factor ($lb/10^{12}$ Btu)	47.5 (0.17-0.23)[d]	83.7	56.0
Concentration in Fuel (ppm)	0.95	0.8-2.0	---

---

[a] Calculated assuming all chromium present in oil feed is emitted through the stack.

[b] Based on typical level of chromium in distillate oil derived in Section 3. Emission factor assumes all chroium present in oil feed is emitted through the stack. A density of 7.05 lb/gal and heating value of 141,000 Btu/gal is assumed.

[c] Calculated total chromium emission factors ($lb/10^{12}$ Btu) for controlled distillate oil-fired boilers are: multiclone, 27.8; ESP, 13.92; scrubber, 3.84. The calculated hexavalent chromium emission factors ($lb/10^{12}$ Btu) for controlled distillate oil-fired boilers are: multiclone, 0.08; ESP, 0.04; scrubber, 0.01. See text for discussion.

[d] The range of values in parentheses are for hexavalent chromium. They were derived by applying the ratio of hexavalent chromium to total chromium emissions (obtained from tests of a coal-fired boiler) to existing emission factors for distillate oil-fired boilers. By sector, the hexavalent chromium emission factors are: industrial boilers, 0.17; commercial boilers, 0.23; residential boilers, 0.20.

TABLE 4-17. MEASURED CHROMIUM EMISSION FACTORS FOR DISTILLATE OIL-FIRED BOILERS

Emission Factor ($lb/10^{12}$ Btu)	Fuel Characteristics		Control Status	Sector[a]	Boiler Type	Reference
	Type	(Chromium Content, ppm)				
2.3-2.5[b]	#2 Oil	---	Uncontrolled	R	Cast Iron[c]	Levy *et al.*, 1971
6.1-9.1[b]	#2 Oil	---	Uncontrolled	R	Cast Iron[c]	Levy *et al.*, 1971
26[d]	Distillate	(1.2)	Uncontrolled	R	Blueray Low NO_x	Castaldini *et al.*, 1981b
370[e]	Distillate	(1.2)	Uncontrolled	R	Blueray Low NO_x	Castaldini *et al.*, 1981b
67.4[f]	Distillate	---	Uncontrolled	R	Conventional High Pressure	Suprenant *et al.*, 1979
3.0	Distillate	(0.38)	Uncontrolled	R	Hot Water Condensing Heating System	Castaldini, 1982

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

[b] Two tests. Calculations assume heating value of 141,000 Btu/gal for #2 oil.

[c] Conversion burner in cast iron boiler - high pressure gun type.

[d] Unit operating in a cycling mode, 10 minutes on, 10 minutes off.

[e] Unit operating continuously.

[f] Eight tests were run for seven units.

TABLE 4-18. CALCULATED UNCONTROLLED COPPER EMISSIONS FROM RESIDUAL OIL-FIRED BOILERS[a]

	Summary Emission Factor[b,c]	Previous Studies				
		Tyndall et al. 1978	Suprenant et al. 1980b	Shih et al. 1980b	Suprenant et al. 1980a	Leavitt et al. 1980b
Emission Factor ($lb/10^{12}$ Btu)	278	149	216	812	67.9	5
Concentration in Fuel (ppm)	5.3	2.8	0.8-9.5	15	---	0.1

[a] Calculated assuming all copper in oil feed is emitted through the stack.

[b] Based on typical level in residual oil derived in Section 3. Emission factor assumes all copper present in oil feed in emitted through the stack. A density of 944 g/l and a heating value of 150,000 Btu/gal are assumed.

[c] Calculated copper emission factors ($lb/10^{12}$ Btu) for controlled residual oil-fired boilers are: multiclone, 165.2; ESP, 42.0; scrubber, 25.2. See text for discussion.

TABLE 4-19. MEASURED COPPER EMISSION FACTORS FOR RESIDUAL OIL-FIRED BOILERS

Emission Factor ($lb/10^{12}$ Btu)	Fuel Characteristics Type	Fuel Characteristics (Copper Content, ppm)	Control Status	Sector[a]	Boiler Type	Reference
13.3	#6 Oil[b]	---	Uncontrolled	C	Scotch with Rotary Burner	Levy *et al.*, 1971
7.4	#5 Oil[b]	---	Uncontrolled	C	Scotch with Air Atomizing Burner	Levy *et al.*, 1971
9.6	#4 Oil[b]	---	Uncontrolled	C	Scotch with Air Atomizing Burner	Levy *et al.*, 1971
48[c]	1:1 Residual/ Crude Oil	(23.0)	Uncontrolled	U	Wall-fired	Sawyer and Higginbotham, 1981b
490[d]	1:1 Residual/ Crude Oil	(53.0)	Uncontrolled	U	Wall-fired	Sawyer and Higginbotham, 1981b
1100[e]	1:1 Residual/ Crude Oil	(16.0)	Uncontrolled	U	Wall-fired	Sawyer and Higginbotham, 1981b
21[c]	#6 Oil	(<3.0)	Uncontrolled	I	Watertube	Carter *et al.*, 1978
24[f]	#6 Oil	(<3.0)	Uncontrolled	I	Watertube	Carter *et al.*, 1978
59[f]	#6 Oil	(<3.0)	Uncontrolled	I	Watertube	Carter *et al.*, 1978

TABLE 4-19. MEASURED COPPER EMISSION FACTORS FOR RESIDUAL OIL-FIRED BOILERS (Continued)

Emission Factor (lb/10^{12} Btu)	Fuel Characteristics Type	Fuel Characteristics (Copper Content, ppm)	Control Status	Sector[a]	Boiler Type	Reference
418[g]	#6 Oil	(1.4)	Multiclone (tested at scrubber inlet)	I	Integral Coal/ Oil Burner	Leavitt et al., 1978b; Fischer et al., 1979
4.6[h]	#6 Oil	(72)	Multiclone/ Scrubber	I	Integral Coal/ Oil Burner	Leavitt et al., 1978b; Fischer et al, 1979

---

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

[b] Calculations assume 146,000 Btu/gal for #4 oil; 148,000 Btu/gal for #5 oil; and 150,000 Btu/gal for #6 oil.

[c] Operating under design (baseline) conditions.

[d] Operating under high level of NO_x control - flue gas is recirculated, top row of burners admit air only (no fuel), lower burner admit fuel at greater than baseline rates.

[e] Flue gas recirculation, all burners in service.

[f] Unit operating under low-NO_x conditions - reduced excess air and maximum flue gas recirculation. Sample analyzed by atomic absorption.

[g] Tested at scrubber inlet of the same boiler as in footnote h.

[h] Tested at scrubber outlet.

The summarized copper emission factor for distillate oil, 280 lb/10^{12} Btu, is essentially the same as the summarized value for residual oil. It is between the distillate oil emission factors calculated in the two previous studies shown in Table 4-20. Table 4-21 summarizes measured emission factors. Five of the six reported measured emission factors are less than 63 lb/10^{12} Btu, well below the summary value; however, the mass balances for the Castaldini et al. (1981b, 1982) tests do not close, with only about 10 to 20 percent of the copper that enters in the oil feed being emitted.

Mercury Emission Factors

The mercury emission factor for residual oil combustion derived in this study is 3.2 lb/10^{12} Btu. This is in close agreement with previously calculated values shown in Table 4-22, which range from 0.47 to 6.67 lb/10^{12} Btu. Measured mercury emission factors are well below calculated factors, ranging from 0.052 to 1.4 lb/10^{12} Btu. Mercury is volatile and it is suspected that a substantial portion of mercury present in the vapor phase escaped detection. For those test runs on Table 4-23 where mass balances can be calculated, only about 3 to 20 percent of the mercury entering in the oil feed was measured in the emissions.

The summary emission factor for mercury from distillate oil combustion is 3.0 lb/10^{12} Btu. This is based on a level of mercury in oil of 0.06 ppm, the same concentration used for residual oil. As described in Section 3, only a single value for the mercury content of distillate oil (0.40 ppm) was recorded in the literature. It was felt that rather than using a single data point to represent all distillate oil, it would be more appropriate to use the same mercury concentration for both residual and distillate oils. This concentration is based on several tests of residual oils (see Section 3). As shown in Tables 4-24 and 4-25, the summary emission factor of 3.0 lb/10^{12} Btu is in close agreement with previously calculated and measured values reported in Suprenant et al. (1980b, 1979). Measured mercury emission factors reported by Castaldini et al. (1981b), are somewhat higher (14-17 lb/10^{12} Btu) due to the higher mercury content of the oil (0.40 ppm).

TABLE 4-20. CALCULATED UNCONTROLLED COPPER EMISSION FACTORS FOR DISTILLATE OIL-FIRED BOILERS[a]

	Summary	Previous Studies	
	Emission Factor[b]	Suprenant et al., 1980b	Suprenant et al., 1980a
Emission Factor ($lb/10^{12}$ Btu)	280[c]	476	87.3
Concentration in Fuel (ppm)	5.6	5.5-11.0	---

[a] Calculated assuming all copper present in oil feed is emitted through the stack.

[b] The calculated copper emission factors ($lb/10^{12}$ Btu) for controlled distillate oil-fired boilers are: multiclone, 165.2; ESP, 42; scrubber, 25.2. See text for discussion.

[c] Based on typical level of copper in distillate oil derived in Section 3. Emission factor assumes all copper present in the oil feed is emitted through the stack. A density of 7.05 lb/gal and a heating value of 141,000 Btu/gal are assumed.

TABLE 4-21. MEASURED COPPER EMISSION FACTORS FOR DISTILLATE OIL-FIRED BOILERS

Emission Factor ($lb/10^{12}$ Btu)	Fuel Characteristics Type	Fuel Characteristics (Copper Content, ppm)	Control Status	Sector[a]	Boiler Type	Reference
6.9-9.2[b]	#2 Oil	---	Uncontrolled	R	Cast Iron[c]	Levy et al., 1971
15.6-17.7[b]	#2 Oil	---	Uncontrolled	R	Cast Iron[c]	Levy et al., 1971
53[d]	Distillate	(11.0)	Uncontrolled	R	Blueray Low NO_x	Castaldini et al., 1981b
63[e]	Distillate	(11.0)	Uncontrolled	R	Blueray Low NO_x	Castaldini et al., 1981b
371.8[f]	Distillate	---	Uncontrolled	R	Conventional High Pressure	Suprenant et al., 1979
5.1	Distillate	(0.47)	Uncontrolled	R	Hot Water Condensing Heating System	Castaldini, 1982

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

[b] Two tests. Calculations assume heating value of 141,000 Btu/gal for #2 oil.

[c] Conversion burner in cast iron boiler - high pressure gun type.

[d] Unit operating in a cycling mode, 10 minutes on, 10 minutes off.

[e] Unit operating continuously.

[f] Eight tests were run for seven units.

TABLE 4-22. CALCULATED UNCONTROLLED MERCURY EMISSION FACTORS FOR RESIDUAL OIL-FIRED BOILERS[a]

	Summary	Previous Studies					
	Emission Factor[b,c]	Tyndall et al. 1978	Suprenant et al. 1980b	Shih et al. 1980b	Leavitt et al. 1980b	Anderson, 1973	Anderson, 1973
Emission Factor (lb/10^{12} Btu)	3.2	2.1	4.4[d]	3.5	5	6.67	0.47
Concentration in Fuel (ppm)	0.06	0.04	0.26[d]	0.066	0.07	0.13	0.009

[a] Calculated assuming all mercury present in oil feed is emitted through the stack.

[b] Calculated from typical level of mercury in residual oil derived in Section 3. Emission factor assumes all mercury present in oil feed is emitted through the stack. A density of 944 g/l and heating value of 150,000 Btu/gal are assumed.

[c] Calculated mercury emission factors (lb/10^{12} Btu) for controlled residual oil-fired boilers are: multiclone, 3.2; ESP, 2.4; scrubber, 0.83. See text for discussion.

[d] There is an apparent discrepancy between the calculated emission factor and the values measured for mercury in the fuel as reported in this reference. The reference states the assumption that all arsenic measured in the oil feed is emitted through the stack, but the numbers presented do not agree with this statement. This discrepancy could not be resolved from the information given in the reference.

TABLE 4-23. MEASURED MERCURY EMISSION FACTORS FOR RESIDUAL OIL-FIRED BOILERS

Emission Factor ($lb/10^{12}$ Btu)	Fuel Characteristics Type	(Mercury Content, ppm)	Control Status	Sector[a]	Boiler Type	Reference
0.23[b]	#6 Oil	---	Multiclone/ Scrubber	I	Integral Coal/ Oil Burner	Leavitt *et al.*, 1978b; Fischer *et al.*, 1979
1.4[b]	#6 Oil	---	Multiclone	I	Integral Coal/ Oil Burner	Leavitt *et al.*, 1978b; Fischer *et al.*, 1979
1.1[c]	#6 Oil	(<0.1)	Uncontrolled	I	Watertube	Carter *et al.*, 1978
1.1[d]	#6 Oil	(<0.1)	Uncontrolled	I	Watertube	Carter *et al.*, 1978
0.037[d]	#6 Oil	(<0.1)	Uncontrolled	I	Watertube	Carter *et al.*, 1978
0.13[c]	1:1 Residual/ Crude	(0.04)	Uncontrolled	U	Wall-fired	Sawyer and Higginbotham, 1981b
0.072[e]	1:1 Residual/ Crude	(0.03)	Uncontrolled	U	Wall-fired	Sawyer and Higginbotham, 1981b
0.052[f]	1:1 Residual/ Crude	(0.04)	Uncontrolled	U	Wall-fired	Sawyer and Higginbotham, 1981b

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

[b] Tested at scrubber inlet and outlet of the same boiler.

[c] Tested under normal or baseline conditions.

[d] Tested under low-NO_x conditions (reduced excess air and flue gas recirculation).

[e] Operated under low-NO_x conditions (flue gas recirculation, top row of burners admit only air, lower burners admit fuel at greater than baseline rates.

[f] Using flue gas recirculation.

TABLE 4-24. CALCULATED UNCONTROLLED MERCURY EMISSION FACTORS FOR DISTILLATE OIL-FIRED BOILERS[a]

	Summary Emission Factor[b,c]	Previous Studies Suprenant et al., 1980b
Emission Factor ($lb/10^{12}$ Btu)	3.0	4.0
Concentration in Fuel (ppm)	0.06	---

[a] Calculated assuming all mercury present in oil feed is emitted through the stack.

[b] Calculated from typical level of mercury in distillate oil derived in Section 3. Emission factor assumes all mercury present in oil feed is emitted through the stack. A density of 7.05 lb/gal and heating value of 141,000 Btu/gal are assumed.

[c] Calculated mercury emission factors ($lb/10^{12}$ Btu) for controlled distillate oil-fired boilers are: multiclone, 3; ESP, 2.25; scrubber, 0.78. See text for discussion.

TABLE 4-25. **MEASURED MERCURY EMISSION FACTORS FOR DISTILLATE OIL-FIRED BOILERS**

Emission Factor (lb/10^{12} Btu)	Fuel Characteristics Type (Hg Content, ppm)	Control Status	Sector[a]	Boiler Type	Reference
2.8[b]	Distillate	Uncontrolled	R	Conventional High Pressure	Suprenant *et al.*, 1979
14[c]	Distillate (0.40)	Uncontrolled	R	Blueray Low NO_x	Castaldini *et al.*, 1981b
17[d]	Distillate (0.40)	Uncontrolled	R	Blueray Low NO_x	Castaldini *et al.*, 1981b

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

[b] Average of eight tests run on seven units.

[c] Unit operating in a cycling mode, 10 minutes on, 10 minutes off.

[d] Unit operating continuously.

Manganese Emission Factors

A summary manganese emission factor of 26 lb/10^{12} Btu was determined for residual oil combustion. This is in the middle range of values calculated in five previous studies (2 to 70.6 lb/10^{12} Btu). The values reported in a sixth study by Suprenant et al. (1980b), shown in Table 4-26, are inconsistent. The calculated emission factor shows 2 1/2 times more manganese being emitted than is input to the boiler in the oil feed.

As shown in Table 4-27, measured manganese emission factors are generally in agreement with the calculated value, ranging from 1.0 to 66 lb/10^{12} Btu with the exception of one reported value of 200 lb/10^{12} Btu. Due to imprecise measurements of manganese in the oil feed, mass balance closures for the test runs cannot be calculated.

The summarized manganese emission factor for distillate oil is 14 lb/10^{12} Btu. This is in close agreement with previously calculated values shown in Table 4-28. Measured emission factors shown in Table 4-29 range from 0.71 to 50 lb/10^{12} Btu, but mass balance closure is poor for the two test runs where it can be calculated.

Nickel Emission Factors

The nickel content of residual oils is relatively high (typically about 24 ppm), and the summarized uncontrolled emission factor is 1,260 lb/10^{12} Btu. This value is in agreement with previously reported values of 500 to 2,240 lb/10^{12} Btu shown in Table 4-30. Eleven measured emission factors summarized in Table 4-31 range from 74 to 3,600 lb/10^{12} Btu. These are in general agreement with calculated factors. For some test runs, mass balances indicate more nickel being emitted than is input in the oil feed. This may be due to corrosion of sampling train components. Corrosion has been suggested as a cause of elevated nickel emissions measurements in similar tests of coal-fired boilers (Baig et al., 1981).

Distillate oil generally contains less nickel than residual oil (typically about 3.4 ppm), and an emission factor of 170 lb/10^{12} Btu is suggested. This is in the same range as previously calculated nickel

TABLE 4-26. CALCULATED UNCONTROLLED MANGANESE EMISSIONS FROM RESIDUAL OIL-FIRED BOILERS[a]

	Summary	Previous Studies					
	Emission Factor[b,c]	Tyndall et al, 1978	Suprenant et al, 1980b	Shih et al, 1980b	Suprenant et al, 1980a	Anderson, 1973	Leavitt et al, 1980b
Emission Factor ($lb/10^{12}$ Btu)	26	70.6	120.8[d]	30.2	19.5	6.7	2
Concentration in Fuel (ppm)	0.49	1.33	0.1-0.98[d]	0.57	---	0.16	0.04

---

[a] Calculated assuming all manganese in oil feed is emitted through the stack.

[b] Based on typical level of manganese in residual oil derived in Section 3. Emission factor assumes all manganese present in oil feed is emitted through the stack. A density of 944 g/l and a heating value of 150,000 Btu/gal are assumed.

[c] Calculated manganese emission factors ($lb/10^{12}$ Btu) for controlled residual oil-fired boilers are: multiclone, 11.96; ESP, 5.72; scrubber, 2.86. See text for discussion.

[d] There is an apparent discrepancy between the calculated emission factor and the values measured for manganese in the fuel as reported in this reference. The reference states the assumption that all arsenic measured in the oil feed is emitted through the stack, but the numbers presented do not agree with this statement. This discrepancy could not be resolved from the information given in the reference.

TABLE 4-27. MEASURED MANGANESE EMISSION FACTORS FOR RESIDUAL OIL-FIRED BOILERS

Emission Factor ($lb/10^{12}$ Btu)	Fuel Characteristics		Control Status	Sector[a]	Boiler Type	Reference
	Type	(Manganese Content, ppm)				
2.7-3.5	#6 Oil[b]	---	Uncontrolled	C	Scotch with Rotary Burner	Levy et al., 1971
2.7-4.0	#5 Oil[b]	---	Uncontrolled	C	Scotch with Air Atomizing Burner	Levy et al., 1971
1.0-2.3	#4 Oil[b]	---	Uncontrolled	C	Scotch with Air Atomizing Burner	Levy et al., 1971
44[c]	1:1 Residual/ Crude Oil	(<1.0)	Uncontrolled	U	Wall-Fired	Sawyer and Higginbotham, 1981b
66[d]	1:1 Residual/ Crude Oil	(<2.0)	Uncontrolled	U	Wall-Fired	Sawyer and Higginbotham, 1981b
200[e]	1:1 Residual/ Crude Oil	(<2.0)	Uncontrolled	U	Wall-Fired	Sawyer and Higginbotham, 1981b
46[c]	#6 Oil	(1.4)	Uncontrolled	I	Watertube	Carter et al., 1978
64[f]	#6 Oil	(<0.5)	Uncontrolled	I	Watertube	Carter et al., 1978
40[f]	#6 Oil	(<0.5)	Uncontrolled	I	Watertube	Carter et al., 1978

TABLE 4-27. MEASURED MANGANESE EMISSION FACTORS FOR RESIDUAL OIL-FIRED BOILERS (Continued)

Emission Factor ($lb/10^{12}$ Btu)	Fuel Characteristics		Control Status	Sector[a]	Boiler Type	Reference
	Type	(Manganese Content, ppm)				
23[g]	#6 Oil	---	Multiclone (tested at scrubber inlet)	I	Integral Coal/ Oil Furnace	Leavitt et al., 1978b; Fischer et al., 1979
3.0[h]	#6 Oil	---	Multiclone/ Scrubber	I	Integral Coal/ Oil Furnace	Leavitt et al., 1978b; Fischer et al., 1979

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

[b] Calculations assume 146,000 Btu/gal for #4 oil; 148,000 Btu/gal for #5 oil; and 150,000 Btu/gal for #6 oil.

[c] Operating under design (baseline) conditions.

[d] Operating under high level of NO_x control - flue gas is recirculated, top row of burners admit air only (no fuel), lower burners admit fuel at greater than baseline rates.

[e] Flue gas recirculation, all burners in service.

[f] Unit operating under low-NO_x conditions - reduced excess air and maximum flue gas recirculation. Sample analyzed by atomic absorption.

[g] Tested at scrubber inlet of same boiler as in footnote h.

[h] Tested at scrubber outlet.

TABLE 4-28. CALCULATED UNCONTROLLED MANGANESE EMISSION FACTORS FOR DISTILLATE OIL-FIRED BOILERS[a]

	Summary Emission Factor[b,c]	Previous Studies	
		Suprenant et al., 1980b	Suprenant et al., 1980a
Emission Factor (lb/10^{12} Btu)	14	14.2	9.8
Concentration in Fuel (ppm)	0.28	0.25-0.3	---

[a] Calculated assuming all manganese present in oil feed is emitted through the stack.

[b] Based on typical level of manganese in distillate oil derived in Section 3. Emission factor assumes all manganese present in oil feed is emitted through the stack. A density of 7.05 lb/gal and heating value of 141,000 Btu/gal is assumed.

[c] Calculated manganese emission factors (lb/10^{12} Btu) for controlled distillate oil-fired boilers are: multiclone, 6.44; ESP, 3.08; scrubber, 1.54. See text for discussion.

TABLE 4-29. MEASURED MANGANESE EMISSION FACTORS FOR DISTILLATE OIL-FIRED BOILERS

Emission Factor (lb/10^{12} Btu)	Fuel Characteristics Type	Fuel Characteristics (Manganese Content, ppm)	Control Status	Sector[a]	Boiler Type	Reference
0.71-1.8[b]	#2 Oil	---	Uncontrolled	R	Cast Iron[c]	Levy _et al._, 1971
0.92-2.4[b]	#2 Oil	---	Uncontrolled	R	Cast Iron[c]	Levy _et al._, 1971
12[d]	Distillate	(17.0)	Uncontrolled	R	Blueray Low NO_x	Castaldini _et al._, 1981b
50[e]	Distillate	(17.0)	Uncontrolled	R	Blueray Low NO_x	Castaldini _et al._, 1981b

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

[b] Two tests. Calculation assumes heating value of 141,000 Btu/gal for #2 oil.

[c] Conversion burner in cast iron boiler - high pressure gun type.

[d] Unit operating in a cycling mode, 10 minutes on, 10 minutes off.

[e] Unit operating continuously.

TABLE 4-30. CALCULATED UNCONTROLLED NICKEL EMISSIONS FROM RESIDUAL OIL-FIRED BOILERS[a]

	Summary Emission Factor[b,c]	Previous Studies					
		Tyndall et al, 1978	Suprenant et al, 1980b	Shih et al, 1980b	Suprenant et al, 1980a	Anderson, 1973; Levy et al, 1971	Leavitt et al, 1980b
Emission Factor ($lb/10^{12}$ Btu)	1260	2240	1870	1004	1690	2000	500
Concentration in Fuel (ppm)	24.0	42.2	10-73	19	---	36.3	8

[a] Calculated assuming all nickel in oil feed is emitted through the stack.

[b] Based on typical level of nickel in residual oil derived in Section 3. Emission factor assumes all nickel present in oil feed is emitted through the stack. A density of 944 g/l and a heating value of 150,000 Btu/gal are assumed.

[c] Calculated nickel emission factors ($lb/10^{12}$ Btu) for controlled residual oil-fired boilers are: multiclone, 642.6; ESP, 352.8; scrubber, 50.4. See text for discussion.

TABLE 4-31. MEASURED NICKEL EMISSION FACTORS FOR RESIDUAL OIL-FIRED BOILERS

Emission Factor (lb/10^{12} Btu)	Fuel Characteristics		Control Status	Sector[a]	Boiler Type	Reference
	Type	(Nickel Content, ppm)				
554	#6 Oil[b]	---	Uncontrolled	C	Scotch with Rotary Burner	Levy *et al.*, 1971
438	#5 Oil[b]	---	Uncontrolled	C	Scotch with Air Atomizing Burner	Levy *et al.*, 1971
329	#4 Oil[b]	---	Uncontrolled	C	Scotch with Air Atomizing Burner	Levy *et al.*, 1971
74[c]	1:1 Residual/ Crude Oil	(26)	Uncontrolled	U	Wall-Fired	Sawyer and Higginbotham, 1981b
1000[d]	1:1 Residual/ Crude Oil	(35)	Uncontrolled	U	Wall-Fired	Sawyer and Higginbotham, 1981b
3600[e]	1:1 Residual/ Crude Oil	(20)	Uncontrolled	U	Wall-Fired	Sawyer and Higginbotham, 1981b
860[c]	#6 Oil	(14)	Uncontrolled	I	Watertube	Carter *et al.*, 1978
1000[f]	#6 Oil	(<10)	Uncontrolled	I	Watertube	Carter *et al.*, 1978
1300[f]	#6 Oil	(<10)	Uncontrolled	I	Watertube	Carter *et al.*, 1978

TABLE 4-31. MEASURED NICKEL EMISSION FACTORS FOR RESIDUAL OIL-FIRED BOILERS (Continued)

Emission Factor ($lb/10^{12}$ Btu)	Fuel Characteristics		Control Status	Sector[a]	Boiler Type	Reference
	Type	(Nickel Content, ppm)				
836[g]	#6 Oil	(16)	Multiclone (tested at scrubber inlet)	I	Integral Coal/ Oil Furnace	Leavitt *et al.*, 1978b; Fischer *et al.*, 1979
146[h]	#6 Oil	(16)	Multiclone/ Scrubber	I	Integral Coal/ Oil Furnace	Leavitt *et al.*, 1978b; Fischer *et al.*, 1979

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

[b] Calculations assume 146,000 Btu/gal for #4 oil; 148,000 Btu/gal for #5 oil; and 150,000 Btu/gal for #6 oil.

[c] Operating under design (baseline) conditions.

[d] Operating under high level of NO_x control - flue gas is recirculated, top row of burners admit air only (no fuel), lower burners admit fuel at greater than baseline rates.

[e] Flue gas recirculation, all burners in service.

[f] Unit operating under low-NO_x conditions - reduced excess air and maximum flue gas recirculation. Sample analyzed by atomic absorption.

[g] Tested at scrubber inlet of same boiler as in footnote h.

[h] Tested at scrubber outlet.

emission factors reported in the literature (see Table 4-32). Measured emission factors reported in Table 4-33 range from 2.7 to 674 lb/10^{12} Btu, but are generally lower than calculated values. For some tests, this appears to be due to lower than average nickel content of the oil feed.

Lead Emission Factors

Emission factors for lead from oil combustion were taken from an EPA background document supporting the national ambient air quality standard (NAAQS) for lead (U. S. Environmental Protection Agency, 1985). In that document, emission factors for distillate and residual oil combustion were presented, based on the concentration of lead in oil (either distillate or residual) and the assumption that 50 percent of the lead in the fuel is emitted to the atmosphere. Separate emission factors for boiler types by sector of boiler use were not included in this reference. Therefore, it was assumed that utility boilers burned residual oil and all other sectors burned distillate oil. All emission factors assume emissions are uncontrolled. Heating values of 150,000 Btu/gal and 141,000 Btu/gallon were used for residual and distillate oil, respectively. Based on these data, the uncontrolled emission factor for lead from utility oil combustion is 28 lb/10^{12} Btu. The uncontrolled emission factor for industrial, commercial, and residential boilers is 8.9 lb/10^{12} Btu.

POM Emission Factors

In the evaluation and comparison of POM emission factors for oil combustion, consideration should be given to:

- the methods used to take and analyze samples,
- the measurement of particulate POM only or of gaseous and particulate POM,
- the physical phase in which emissions predominantly occur,
- the number of POM compounds analyzed for, and
- the specific POM compounds analyzed for.

TABLE 4-32. CALCULATED UNCONTROLLED NICKEL EMISSION FACTORS FOR DISTILLATE OIL-FIRED BOILERS[a]

	Summary Emission Factor[b,c]	Previous Studies	
		Suprenant, 1980b	Suprenant et al., 1980a
Emission Factor ($lb/10^{12}$ Btu)	170	260.3	106
Concentration in Fuel (ppm)	3.4	1-18	---

[a] Calculated assuming all nickel present in oil feed is emitted through the stack.

[b] Based on typical level of nickel in distillate oil derived in Section 3. Emission factor assumes all nickel present in oil feed is emitted through the stack. A density of 7.05 lb/gal and heating value of 141,000 Btu/gal is assumed.

[c] Calculated nickel emission factors ($lb/10^{12}$ Btu) for controlled distillate oil-fired boilers are: mutliclone, 86.7; ESP, 47.6; scrubber, 6.8. See text for discussion.

TABLE 4-33. MEASURED NICKEL EMISSION FACTORS FOR DISTILLATE OIL-FIRED BOILERS

Emission Factor (lb/10^{12} Btu)	Fuel Characteristics		Control Status	Sector[a]	Boiler Type	Reference
	Type	(Nickel Content, ppm)				
2.7-2.9[b]	#2 Oil	---	Uncontrolled	R	Cast Iron[c]	Levy et al., 1971
3.1-3.4[b]	#2 Oil	---	Uncontrolled	R	Cast Iron[c]	Levy et al., 1971
22[d]	Distillate	(0.09)	Uncontrolled	R	Blueray Low NO_x	Castaldini et al., 1981b
36[e]	Distillate	(0.09)	Uncontrolled	R	Blueray Low NO_x	Castaldini et al., 1981b
674[f]	Distillate	---	Uncontrolled	R	Conventional High Pressure	Suprenant et al., 1979
7.6	Distillate	(0.93)	Uncontrolled	R	Hot Water Condensing Heating System	Castaldini, 1982

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

[b] Two tests. Calculation assumes heating value of 141,000 Btu/gal for #2 oil.

[c] Conversion burner in cast iron boiler - high pressure gun type.

[d] Unit operating in a cycling mode, 10 minutes on, 10 minutes off.

[e] Unit operating continuously.

[f] Eight tests were run on seven units.

The literature contains POM emission factor data that span from the early 1960s to the present. The methods used in the past source tests to sample and analyze POM compounds from combustion sources have varied considerably with respect to sample collection, preservation, preparation, and component analysis techniques. Because of this variability, it is often difficult to make valid comparisons of POM emission results because the forms, species, and sensitivity of measurements may be grossly different between tests even though both report a total POM result.

One important factor affecting the comparability of results involves whether the sample collection technique attempted to collect gaseous as well as particulate POM. Many of the earlier source tests used only a standard EPA Method 5 sample collection procedure and thus did a less than adequate job of collecting many POM compounds emitted in gaseous form. More recently, a Modified Method 5 approach has become popular for combustion source testing. The Modified Method 5 approach employs a resin filter to trap condensible organics including POM. Because gaseous POM have been shown to often be dominant in total combustion source POM emissions, the inclusion of a gaseous POM collection procedure is important. Knowing the physical forms of POM sampled for in a test is crucial to being able to compare one test's results with those of another test of the same or similar source.

In the evaluation and comparison of any total POM emissions data, some definition must be known or established as to what constitutes total POM. As discussed, the number of POM compounds that conceivably may be formed during combustion processes runs into the hundreds. Few, if any, source tests analyze for that many compounds. The majority of the combustion source POM emission tests in the literature analyzed for less than 25 specific POM compounds. The largest number of compounds analyzed for was 56. When one test analyzed for only 10 POM compounds and one other for 25 POM compounds, total POM results will not be comparable between the two tests.

In assessing the number of specific POM compounds analyzed, the specific compounds analyzed for should also be carefully evaluated. In many combustion source tests for POM emissions, the 25 POM compounds expected to occur in the largest quantity are analyzed for. Other tests, however, analyze for POM compounds on the basis of compound toxicity such that several compounds that may occur in only minute proportions, but are highly toxic, are analyzed for at the expense of high volume/low toxicity compounds. A good example of this situation was seen in several tests where naphthalene was and was not analyzed for. Naphthalene generally constituted a sizable portion of total POM emissions in the tests where it was measured. However, in terms of other POM compounds [e.g., benzo(a)pyrene], it is viewed as having a low toxicity. Other tests, more concerned with the quantification of toxic POM emissions from combustion sources, did not include naphthalene in the list of analyzed compounds and, therefore, had a significantly lower total POM value than those that did. The exclusion or inclusion of specific compounds can therefore be highly important in the evaluation and comparison of POM emissions data.

Despite the problems and considerations outlined above which influence the ability to define total POM and compare POM results between different source tests, the summarized oil combustion POM data in Table 4-34 are presented without regard to differentiating the POM species tested for, the test methods used, etc. These differentiations were not possible to make given the scope of this document. The data in Table 4-34 are presented to illustrate what has been reported in the literature as total POM emissions from oil combustion. The reader can judge the level of inconsistency in the summary total POM data (Table 4-34) by reviewing the constituent individual source test results given in Tables 4-35 and 4-36.

As discussed, summarized POM emission factors for oil combustion are derived from measured emission factors reported in the literature. There is no reliable method for quantitatively predicting POM emissions. POM emission factors from tests of fifteen uncontrolled residual oil-fired boilers in the utility, industrial, and commercial sectors were available in the literature. As summarized in Table 4-34, the average POM emission factor for these tests is 8.4 lb/10^{12} Btu, with factors for the 15 boilers ranging from 0.07 to 77.3 lb/10^{12} Btu. Information on each test is recorded in Table 4-35. Based on these limited data, boiler type and combustion sector did not appear to influence POM emission factors significantly.

As shown in Tables 4-34 and 4-35, a POM emission factor of 5.8 lb/10^{12} Btu was measured at one utility boiler controlled with a cyclone. Polycyclic organic matter emissions were not detected from another utility

TABLE 4-34. SUMMARY OF TOTAL POM EMISSION FACTORS FOR OIL COMBUSTION

Type of Oil/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Emission Factor ($lb/10^{12}$ Btu) Range	Number of Boilers Tested
Residual Oil:			
Uncontrolled	8.4[a]	0.07-77.3[a]	17
Cyclones	---	5.8	1
Distillate Oil:			
Uncontrolled	<22.5	<0.28-41.2	5

[a] The upper end of the range, 77.3 $lb/10^{12}$ Btu, could be considered an outlier from the rest of the range; however, nothing in the test report suggested this to be the case. If this value is excluded when calculating an average emission factor, the average factor is only 4.1 $lb/10^{12}$ Btu.

TABLE 4-35. MEASURED TOTAL POM EMISSION FACTORS FROM RESIDUAL OIL COMBUSTION

Boiler Type	Boiler Application	Controls Used	Total POM Emission Factor $lb/10^{12}$ Btu-heat Input	Reference
Tangential-Fired	Electric Utility	None	77.3[a,b]	Shih *et al.*, 1980b
Wall-Fired	Electric Utility	None	1.3[a,c]	Shih *et al.*, 1980b
Wall-Fired	Electric Utility	None	28.6[a,d]	Shih *et al.*, 1980b
Wall-Fired	Electric Utility	None	1.0[a,e]	Shih *et al.*, 1980b
Wall-Fired	Electric Utility	None	5.9[a,f]	Shih *et al.*, 1980b
Face-Fired	Electric Utility	None	4.8[g]	DeAngelis and Piper, 1981
Not Reported	Electric Utility	None	10.2[h]	DeAngelis and Piper, 1981
Face-Fired	Electric Utility	None	0.75[i]	DeAngelis and Piper, 1981
Face-Fired	Electric Utility	None	0.98[j]	DeAngelis and Piper, 1981
Tangential-Fired	Electric Utility	Cyclones	5.8[a,k]	Shih *et al.*, 1980b
Not Reported	Electric Utility	None	0.066 - 2.1[l]	Zelenski *et al.*, 1980a
Steam Atomized Watertube	Industrial Heating	None	5.4[m]	Hangebrauck *et al.*, 1964
Watertube	Industrial Heating	None	1.5[a,n]	Suprenant *et al.*, 1980a
Scotch Marine	Commercial Heating	None	2.2[o]	Suprenant *et al.*, 1980a

[a] Factor represents both particulate and gaseous POM emissions. Fifty-six specific POM compounds were analyzed for during these tests. Test operated under low-NO_x conditions (off-stoichiometric firing and flue gas recirculation).

[b] Specific compounds identified were naphthalene and biphenyl. Naphthalene accounted for 96 percent of total POM emissions.

[c] Specific compounds identified were 2-ethyl-1,1-biphenyl and naphthalene. 2-Ethyl-1,1-biphenyl accounted for 64 percent of total POM emissions and naphthalene 36 percent.

[d] Specific compounds identified were naphthalene and biphenyl. Naphthalene constituted 94 percent of total POM emissions and biphenyl 6 percent.

[e] Specific compounds identified were 2-ethyl-1,1-biphenyl and 1,2,3-trimethyl-4-propenyl naphthalene, each of which constituted 50 percent of total POM emissions.

[f] Specific compounds identified were naphthalene, phenanthridine, dibenzothiophene, anthracene/phenanthrene, fluoranthene, pyrene, chrysene/benz(a)anthracene, benzopyrene/perylenes, and tetramethyl phenanthrene. The primary constituents of total POM emissions were naphthalene (67 percent), anthracene/phenanthrene (8 percent), fluoranthene (7 percent), pyrene (7 percent), and tetramethyl phenanthrene (4 percent).

[g] Factor represents primarily particulate POM emissions. Specific compounds identified were phenanthrene, anthracene, methyl anthracenes/phenanthrenes, fluoranthrene, pyrene, methyl pyrene/fluoranthene, benzo(c)phenanthrene, benzo(a)anthracene, chrysenes, methyl chrysenes, benzofluoranthenes, benzo(e)pyrene, benzo(a)pyrene, perylene, indeno-pyrene, coronene, and benzo(g,h,i)perylene. The primary constituents of total POM emissions were phenanthrene (16 percent), methyl anthracenes/phenanthrenes (13 percent), fluoranthene (8 percent), and pyrene (7 percent).

TABLE 4-35. MEASURED TOTAL POM EMISSION FACTORS FROM RESIDUAL OIL COMBUSTION (Continued)

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[h] Factor represents primarily particulate POM emissions. Specific compounds identified were phenanthrene, anthracene, methyl anthracenes/phenanthrenes, fluoranthene, pyrene, methyl pyrene/fluoranthene, benzo(c)phenanthrene, benzo(a)anthracene, chrysenes, benzofluoranthenes, benzo(e)pyrene, and benzo(a)pyrene. The primary constituents of total POM emissions were phenanthrene (51 percent), fluoranthene (14 percent), benzo(g,h,i)perylene (9 percent), and methyl anthracenes/phenanthrenes (7 percent).

[i] Factor represents both particulate and gaseous POM emissions. Specific compounds identified were phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, and chrysene. The primary constitutents of total POM emissions were phenanthrene (35 percent), anthracene (31 percent), fluoranthene (14 percent), and pyrene (14 percent). Approximately 63 percent of total POM emissions were measured in the gaseous phase.

[j] Factor represents both particulate and gaseous POM emissions. Specific compounds identified were phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, and chrysene. The primary constituents of total POM emissions were phenanthrene (34 percent), anthracene (31 percent), fluoranthene (15 percent), and pyrene (12 percent). Approximately 65 percent of total POM emissions were measured in the gaseous phase. Test was conducted under low-NO_x burn conditions.

[k] Specific compounds identified were naphthalene and biphenyl. Naphthalene constituted 72 percent of total POM emissions and biphenyl 28 percent.

[l] Factor represents both particulate and gaseous POM emissions. Twenty-one specific POM compounds were analyzed for during these tests. The principal constituents of total POM emissions were anthracene/phenanthrene (53 percent), fluoranthene (17 percent), pyrene (15 percent), and methyl anthracenes (5 percent).

[m] Factor represents primarily particulate POM emissions. Specific compounds identified were benzo(a)pyrene, pyrene, phenanthrene, and fluoranthene. Phenanthrene constituted about 75 percent of total POM emissions, pyrene 12 percent, and fluoranthene 11 percent.

[n] This factor is for biphenyl emissions only. No other POM compounds were measured during these tests. This is an average emission factor for five boilers, four of which are uncontrolled and one which is controlled by a cyclone/scrubber combination.

[o] This factor is for benzo(a)pyrene only. No other POM compounds were measured during these tests.

TABLE 4-36. MEASURED UNCONTROLLED TOTAL POM EMISSION FACTORS FROM DISTILLATE OIL COMBUSTION

Boiler Type	Boiler Application	Total POM Emission Factor lb/10^{12} Btu-heat input[a]	Reference
Watertube	Process Heating	<0.28[b]	Hangebrauck *et al.*, 1964
Scotch Marine	Hospital Heating	41.2[c]	Hangebrauck *et al.*, 1964
Cast Iron Sectional	Home Heating	<34.6[d]	Hangebrauck *et al.*, 1964
Hot Air Furnace	Home Heating	<0.33[e]	Hangebrauck *et al.*, 1964
Hot Air Furnace	Home Heating	<35.9[f]	Hangebrauck *et al.*, 1964

[a] Factors represent primarily particulate POM emissions. Eleven specific POM compounds were analyzed for during these tests.

[b] Specific compounds identified were benzo(a)pyrene, pyrene, and fluoranthene. Fluoranthene accounted for 45 percent of total POM emissions, pyrene 39 percent, and benzo(a)pyrene 16 percent.

[c] Specific compounds identified were benzo(a)pyrene, pyrene, benzo(g,h,i)perylene, coronene, anthracene, phenanthrene, and fluoranthene. Primary constituents of total POM emissions were pyrene (33 percent), anthracene (21 percent), phenanthrene (19 percent), and coronene (11 percent).

[d] Specific compounds identified were benzo(a)pyrene, pyrene, and phenanthrene, and fluoranthene. Phenanthrene constituted 57 percent of total POM emissions, fluoranthene 32 percent, and pyrene 11 percent.

[e] Specific compounds identified were benzo(a)pyrene, pyrene, and fluoranthene. Fluoranthene constituted 50 percent of total POM emissions, benzo(a)pyrene 40 percent, and pyrene 10 percent.

[f] Specific compounds identified were benzo(a)pyrene, pyrene, and fluoranthene. Fluoranthene accounted for 92 percent of total POM emissions, pyrene 7 percent, and benzo(a)pyrene 1 percent.

boiler equipped with a cyclone and from two utility boilers equipped with ESPs. While test results for these four boilers may indicate lower POM emission factors for boilers equipped with particulate control devices, this is uncertain since uncontrolled emission factors for the four boilers are not available for comparison, and the minimum POM detection limit of the sampling and analysis methodologies for these test runs is unknown. Based on theoretical considerations it is believed that a substantial portion of POM emissions would be present in vapor form in the flue gas and would escape collection by particulate control devices.

Measured POM emission factors for five distillate oil-fired boilers are available. Specifics of each test are listed in Table 4-36. Three of the tests were on residential furnaces. A commercial/institutional boiler and an industrial boiler were also tested. As shown in Tables 4-34 and 4-36, the average POM emission factor for these five tests is approximately 22.5 lb/10^{12} Btu. Emission factors ranged from less than 0.28 for the industrial boiler to 41.2 lb/10^{12} Btu for the commercial boiler. Emission factors for the residential furnaces ranged from less than 0.33 to less than 35.9 lb/10^{12} Btu.

Formaldehyde Emission Factors

Formaldehyde emission factors are based on emissions testing since there is no reliable method for calculating quantitative emission factors. Only four measured emission factors for oil-fired combustion sources were available in the literature. These are summarized in Table 4-37. Reported emission factors ranged from 160 to 640 lb/10^{12} Btu, with the average value being 405 lb/10^{12} Btu.

EMISSION FACTORS FOR COAL-FIRED COMBUSTION SOURCES

Emission factors for coal-fired sources are derived from a combination of measured data and calculated emission factors. The literature was reviewed for test data from which trace element emission factors (in terms of pounds emitted per 10^{12} Btu of coal input) could be derived. About 35

TABLE 4-37. MEASURED FORMALDEHYDE EMISSION FACTORS FOR OIL-FIRED BOILERS AND FURNACES

Emission Factor (lb/10^{12} Btu)	Fuel Characteristics	Control Status	Sectors[a]	Boiler Type	Reference
240	#2 Oil	Uncontrolled	I	Steam Atomized	Hangebrauck _et al._, 1964
640	#2 Oil	Uncontrolled	R	Centrifugal Atomized	Hangebrauck _et al._, 1964
580	#1 Oil	Uncontrolled	R	Vaporized	Hangebrauck _et al._, 1964
160	#6 Oil	Uncontrolled	I	Steam Atomized	Hangebrauck _et al._, 1964

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

references reported measured emission factors for one or more of the trace pollutants and types of combustion sources under study. Procedures for calculating trace element emissions were also reviewed. The utility and industrial sectors are the best characterized combustions sectors, while relatively few test data are available for the commercial/institutional and residential sectors. Trace metal and POM emissions are considerably better characterized in the literature than radionuclide and formaldehyde emissions.

The trace pollutant emission factors presented for coal combustion should be viewed as realistic average estimates based on the available data. It should be recognized that there is considerable uncertainty in these estimates due to the wide variability in trace element levels in coal (see Section 3), variations in the design and operating parameters of boilers and control devices, and uncertainty in sampling and analytical methodologies for detecting trace pollutants.

Also, it may be difficult to compare emission factors for different control technologies for a given trace element because of the limited data. In some cases, only a single test result was available from which to report an emission factor for a particular boiler type/control technique pair. Thus, some values reported in the summary tables may seem incongruous, when actually, they reflect the data available in the literature.

Trace Metal Emission Factors

In general, the sources of data and procedures for deriving emission factors are similar for the nine trace metals under study. Summarized emission factors are presented and compared with previously measured and calculated values.

The summarized emission factors should not be construed to represent a fully characterized or representative emission rate for the given combustion source situation. Extensive data quality assurance procedures, necessary to reasonably characterize a data set as representative of a particular source, were not performed in this study because of time and budgetary constraints. Instead, the summarized factors are simply straightforward calculations of emission factor averages and ranges based on data presented in the literature. The summarized factors are not to be considered as suggested emission factor values for use in other activities such as regulatory development or specification of acceptable ambient concentrations.

Due to the relatively greater availability of test data for bituminous coal-fired utility and industrial boilers, summary emission factors for bituminous coal combustion can generally be derived from test data. The data indicate that for similar types of boilers and control devices, emission factors between the utility and industrial sectors are similar. There is a lack of data on trace metal emissions for the commercial/institutional sector. However, the boilers used in this sector are similar in size and design to the smaller industrial boilers. Therefore, emission factors for commercial/institutional boilers can be derived from information on the other combustion sectors. There is also a lack of data on lignite and anthracite combustion, so emission factors for these types of coal must be calculated.

Trace metal emission factors for coal-fired residential furnaces are described. A calculation procedure based on the trace metal content of coal and on partitioning data from a limited number of tests of residential furnaces is used to derive emission factors for each of the trace metals (excluding lead). The summarized emission factors for each trace metal are compared with previously reported emission factors.

Arsenic Emission Factors-

Table 4-38 presents summarized arsenic emission factors for utility, industrial, and commercial/institutional boilers. Where possible, these were derived from emissions tests at representative boilers. The data base is summarized in Tables 4-39 through 4-44. For each sector/coal type/boiler design/control technology combination, the average arsenic emission factor and range of emission factors found in the literature are presented. The number of boilers and number of test runs from which these averages are derived are also included in the tables. More detailed information on each test, including the test references, are included in Appendix C, Tables C-1 through C-9.

TABLE 4-38. SUMMARIZED ARSENIC EMISSION FACTORS FOR COAL-FIRED BOILERS

Boiler Type/Control Status	Emission Factor ($lb/10^{12}$ Btu) by Coal Type Bituminous	Lignite	Anthracite
Pulverized Dry Bottom:			
Uncontrolled	684	1390	266
Multiclone	335	683	130
ESP	40.1	82	15.6
Scrubber	17.2	35	6.7
Pulverized Wet Bottom:			
Uncontrolled	538	2730	521
Multiclone	264	1340	256
ESP	67.2	343	65
Scrubber	76.7	156	29.8
Cyclone:			
Uncontrolled	115-310	235-632	45-121
Multiclone	56-152	114-310	22-59
ESP	14.4	29	5.6
Spreader Stoker:			
Uncontrolled	264-542	538-1100	103-210
Multiclone	129-265	263-540	50-103
ESP	33-67	67-137	13-26
Overfeed Stoker:			
Uncontrolled	542-1030	1100-2100	210-401
Multiclone	265-505	540-1030	103-196
ESP	67-129	137-263	26-50

TABLE 4-39. SUMMARY OF MEASURED ARSENIC EMISSION FACTORS FOR BITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type/Control Status	Emission Factor (lb/10^{12} Btu)		Number of Boilers Tested	Number of Data Points
	Average[a]	Range		
Pulverized Dry Bottom:				
Uncontrolled	684	62-1360	5	20
Mechanical Precipitator	653	19-1980	2	10
ESP, or Mechanical Ppt. followed by ESP	40.1	0.35-242	15	37
Mechanical Ppt/2 ESPs in Series	6.1	0.29-13.2	1	5
Scrubber	17.2	3.95-31.4	4	6
ESP/Scrubber	14.9	---	1	1
Pulverized Wet Bottom:				
ESP or Mechanical Ppt. followed by ESP	67.2	15.3-165	4	4
Scrubber	76.7	---	1	1
Cyclone:				
Uncontrolled	310	130-490	1	2
ESP	14.4	6.3-27.9	5	6
Scrubber	813	---	1	1
Stoker:				
Mechanical Ppt. or Multiclone	3006	432-5580	2	2
Fabric Filter	0.77	---	1	1

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[a] Each boiler tested was weighted equally in determining this average. An arthmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-40. SUMMARY OF MEASURED ARSENIC EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu)		Number of Boilers	Number of Data Points
	Average	Range		
Pulverized Coal-Fired:				
ESP	0.17	---	1	1
Scrubber	11	---	1	1
Cyclone:				
Uncontrolled	860	---	1	1
Scrubber	810	---	1	1
Unspecified Boiler Type:				
ESP	6.2	2.4-10	2	2

TABLE 4-41. SUMMARY OF MEASURED ARSENIC EMISSION FACTORS FROM LIGNITE COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu)		Number of Boilers	Number of Data Points
	Average	Range		
Pulverized Dry Bottom:				
Multiclone	382	367-397	2	2
ESP	<2.3	---	1	1
Cyclone:				
Multiclone	270	---	1	1
ESP	5.8	---	1	1
ESP/Scrubber	11.2	---	1	1
Spreader Stoker:				
Multiclone	265	---	1	1
ESP	<5.3	---	1	1

TABLE 4-42. SUMMARY OF MEASURED ARSENIC EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Uncontrolled	690	---	1	2
Multiclone	7900	---	1	1
Multiclone/Scrubber	214	---	1	1
ESP	44.6	15.8-120	5	6
Pulverized Wet Bottom:				
Multiclone	32.5	---	1	1
Spreader Stoker:				
Uncontrolled	264	0.27-835	7	14
Multiclone	478	102-853	2	2
Multiclone/ESP	43.4	31-53.7	2	3
Overfeed Stoker:				
Uncontrolled	1030	60-2600	4	5
Economizer/Dust Collector	395	370-420	1	2

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[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-43. SUMMARY OF MEASURED ARSENIC EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Number of Boilers	Number of Data Points
Spreader Stoker:				
Uncontrolled	217	68-490	2	4
Mechanical Ppt/ESP	4.4	3.0-5.8	1	2

[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-44. SUMMARY OF MEASURED ARSENIC EMISSION FACTORS FOR COMMERCIAL/INSTITUTIONAL COAL-FIRED BOILERS

		Emission Factor ($lb/10^{12}$ Btu)			
Coal Type/ Boiler Type	Control Status	Average[a]	Range	Number of Boilers	Number of Data Points
Bituminous Coal:					
Pulverized Dry Bottom	Uncontrolled	4470	---	1	1
	Multiclone/ Scrubber	51.1	---	1	1
Underfeed Stoker	Uncontrolled	4.2	---	1	1
Spreader Stoker	Mechanical Ppt	11.6	---	1	1
Overfeed Stoker	Mechanical Ppt	25.6	---	1	1
Anthracite Coal:					
Stoker	Uncontrolled	137	5.3-235	3	3

Bituminous Coal-Fired Pulverized Dry Bottom Boilers. The summary arsenic emission factor for uncontrolled pulverized dry bottom boilers is 684 lb/10^{12} Btu. This is the average emission factor for tests of uncontrolled emissions from five utility boilers reported in the literature (see Table 4-39). This factor is in agreement with the emission factor of 690 lb/10^{12} Btu measured at one uncontrolled industrial pulverized dry bottom boiler in the data base (Table 4-40). It is also in general agreement with the previously calculated emission factors shown in Table 4-45. The only commercial/institutional boiler of this description tested had a higher emission factor (Table 4-44). The level of arsenic in the coal was not reported for that test, and the causes of the higher emissions measurement could not be determined.

Only three pulverized dry bottom boilers with mechanical precipitators (multiclones) were tested - two utility and one industrial boiler (see Tables 4-39 and 4-42). A meaningful average cannot be derived from these tests. One boiler tested had extremely low arsenic emissions (19 to 49 lb/10^{12} Btu) and the other two had arsenic emissions which were higher than any of the uncontrolled boilers tested (over 1000 lb/10^{12} Btu). The industrial boiler which had the highest emission factor was burning high arsenic coal (137 ppm as opposed to an average of 20.3 ppm for bituminous coal). However, the two utility boilers were burning coal of similar arsenic content (13-19 ppm). It is uncertain whether boiler and control design and operating parameters, sampling methodology, or both, account for the discrepancy.

Since the data are limited and inconsistent, the summary emission factor for bituminous coal-fired pulverized dry bottom boilers was derived by applying a control percentage to the uncontrolled emission factor. As shown on Table 4-46, testing of a mechanical precipitator on a combustion source showed an average control efficiency of 51 percent. This control efficiency is consistent with theory. For overall particulate control, multiclones can achieve greater efficiencies (Shih et al. (1980b) estimated 70.2 percent), but they are less efficient at controlling smaller particles, and arsenic is enriched on small fly ash particles. Applying the 51 percent control factor to the uncontrolled emission factor of 684 lb/10^{12} Btu, an

TABLE 4-45. CALCULATED ARSENIC EMISSION FACTORS FOR COAL COMBUSTION

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor ($lb/10^{12}$ Btu)	Reference
Bituminous	Pulverized Dry Bottom	Uncontrolled	U, I, C	630-670	Baig *et al.*, 1981
Bituminous	Pulverized Dry Bottom	Uncontrolled	I, C	2790	Suprenant *et al.*, 1980b Suprenant *et al.*, 1980a
Bituminous	Pulverized Dry Bottom	Mechanical Ppt.	U	823	Shih *et al.*, 1980b
Bituminous	Pulverized Dry Bottom	Cyclone	I	813	Suprenant *et al.*, 1980a
Bituminous	Pulverized Dry Bottom	ESP	U, I	58.8	Baig *et al.*, 1981; Shih *et al.*, 1980b
Bituminous	Pulverized Dry Bottom	Wet Scrubber	U	48.8	Shih *et al.*, 1980b
Bituminous	Pulverized Wet Bottom	Uncontrolled	U, I	510-790	Baig *et al.*, 1981
Bituminous	Pulverized Wet Bottom	Mechanical Ppt.	U	669	Shih *et al.*, 1980b
Bituminous	Pulverized Wet Bottom	Multiclone	U, I	150	Baig *et al.*, 1981
Bituminous	Pulverized Wet Bottom	ESP	U, I	48.8	Baig *et al.*, 1981; Shih *et al.*, 1980b
Bituminous	Pulverized Wet Bottom	Wet Scrubber	U	44.2	Shih *et al.*, 1980b
Bituminous	Cyclone	Uncontrolled	U	110-790	Baig *et al.*, 1981
Bituminous	Cyclone	Mechanical Ppt.	U	139	Shih *et al.*, 1980b
Bituminous	Cyclone	ESP	U	10	Baig *et al.*, 1981; Shih *et al.*, 1980b
Bituminous	Cyclone	Wet Scrubber	U	8.1	Shih *et al.*, 1980b

TABLE 4-45. CALCULATED ARSENIC EMISSION FACTORS FOR COAL COMBUSTION (Continued)

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor ($lb/10^{12}$ Btu)	Reference
Bituminous	Stoker	Uncontrolled	U, I, C	460-790	Baig _et_ _al._, 1981
Bituminous	Stoker	Multiclone	U, I, C	140	Baig _et_ _al._, 1981
Bituminous	Spreader Stoker	Uncontrolled	I	2140	Suprenant _et_ _al._, 1980a
Bituminous	Spreader Stoker	Cyclone	I	627	Suprenant _et_ _al._, 1980a
Bituminous	Underfeed Stoker	Uncontrolled	C	232	Suprenant _et_ _al._, 1980b
Bituminous	Automatic Coal-Fired Furnace	Uncontrolled	R	1550	DeAngelis and Reznik, 1979
Lignite	Pulverized Dry Bottom	Uncontrolled	U, I, C	200-580	Baig _et_ _al._, 1981
Lignite	Pulverized Dry Bottom	Multiclone	U, I, C	53	Baig _et_ _al._, 1981
Lignite	Pulverized Dry Bottom	Mechanical Ppt.	U	34.9	Shih _et_ _al._, 1980b
Lignite	Pulverized Dry Bottom	ESP	U	8.1	Shih _et_ _al._, 1980b
Lignite	Pulverized Dry Bottom	Wet Scrubber	U	34.9	Shih _et_ _al._, 1980b
Lignite	Cyclone	Uncontrolled	U	170-580	Baig _et_ _al._, 1981
Lignite	Cyclone	Mechanical Ppt.	U	216	Shih _et_ _al._, 1980b
Lignite	Cyclone	ESP	U	4.4	Shih _et_ _al._, 1980b
Lignite	Cyclone	Wet Scrubber	U	19.3	Shih _et_ _al._, 1980b
Lignite	Stoker	Uncontrolled	U, I, C	200-580	Baig _et_ _al._, 1981

TABLE 4-45. CALCULATED ARSENIC EMISSION FACTORS FOR COAL COMBUSTION (Continued)

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor ($lb/10^{12}$ Btu)	Reference
Lignite	Stoker	Multiclone	U, I, C	53	Baig et al., 1981
Lignite	Automatic Coal-Fired Furnace	Uncontrolled	R	696	DeAngelis and Reznik, 1979
Anthracite	Pulverized Dry Bottom	Uncontrolled	U, I, C	440-510	Baig et al., 1981
Anthracite	Stoker	Uncontrolled	U, I, C	25-510	Baig et al., 1981
Anthracite	Stoker	Uncontrolled	C	116	Suprenant et al., 1980b
Anthracite	Automatic Coal-Fired Furnace	Uncontrolled	R	391	DeAngelis and Reznik, 1979

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[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

TABLE 4-46. ARSENIC REMOVAL EFFICIENCY OF CONTROLS[a]

Control Device	% Control Efficiency Average[b]	 Range	Number of Boilers	Number of Test Runs
Mechanical Ppt.	51.0	25.8-70.8	1	3
ESP	87.5	50.0-97.6	7	21
FGD Scrubber	---	5.8-97.3	2	2
ESP/Scrubber	98.9	---	1	1
2 ESPs in Series	99.6	99.2-99.97	1	5

[a] These control efficiencies represent measured control levels reported in the literature. They may or may not be indicative of the long-term performance of these types of controls on arsenic emissions from combustion sources. The average values should not be construed to represent an EPA-recommended efficiency level for these devices.

[b] Each emission test weighted equally.

emission factor of 335 lb/10^{12} Btu is obtained for pulverized dry bottom boilers controlled with mechanical precipitators.

The summary emission factor for ESP-controlled pulverized dry bottom boilers, 40.1 lb/10^{12} Btu, is an average of 37 tests run on 15 utility boilers (Table 4-39). Tests of industrial boilers (Table 4-42) yield a similar average. The scrubber controlled emission factor is 17.2 lb/10^{12} Btu, based on six tests of four utility boilers. These emission factors are in agreement with previously calculated values shown in Table 4-45.

Bituminous Coal-Fired Pulverized Wet Bottom Boilers. Data from four boilers show that the average emission factor for ESP-controlled pulverized wet bottom boilers is 67.2 lb/10^{12} Btu. There is a lack of data for pulverized wet bottom boilers controlled by other means. The percent arsenic control efficiencies of ESPs and multiclones measured in the literature are presented in Table 4-46. Using these control efficiencies and the 67.2 lb/10^{12} Btu factor for ESP- controlled boilers, the uncontrolled emission factor would be 538 lb/10^{12} Btu and the mechanical precipitator- (or multiclone-) controlled emission factor would be 264 lb/10^{12} Btu. Calculations support these factors.

If all of the arsenic in typical bituminous coal (20.3 ppm) were emitted during combustion, the maximum uncontrolled emission factor would be 1,560 lb/10^{12} Btu, assuming a heat content of 13,077 Btu/lb. If arsenic was emitted in the same proportion as total particulates, an uncontrolled emission factor of 1,010 lb/10^{12} Btu would be expected. This assumes 65 percent of the ash is emitted as fly ash (Baig et al., 1981). Since arsenic is preferentially concentrated in the fly ash, an emission factor between these two values would be expected.

The emission factor data for ESP-controlled wet bottom units is inconsistent with what would theoretically be expected in relation to ESP-controlled dry bottom units. Since wet bottom boilers have a lower fly ash to bottom ash ratio than dry bottom boilers (65:35 vs 80:20), it would be expected that uncontrolled and controlled emissions of arsenic would be higher for dry bottom units provided all other emission-affecting variables between the two boilers were constant. The data available for this report show an ESP-controlled dry bottom boiler factor of 40.1 lb/10^{12} Btu as opposed to a 67.2 factor for wet bottom units. This discrepancy is probably a function of the limited emissions data base for wet bottom boilers controlled by ESP's. There were only four test values from which to base the wet bottom number, while the dry bottom factor was based on 37 data points. With such a limited basis for wet bottom units, it is unlikely that a truly representative average could be determined. Where more precise information is needed for an ESP-controlled wet bottom boiler, the reader is advised to seek out additional, more current test data that may be available or conduct site-specific testing.

Bituminous Coal-Fired Cyclone Boilers. Cyclone boilers controlled with ESPs emit an average of 14.4 lb/10^{12} Btu. The lower emission factor for cyclone boilers as opposed to pulverized coal boilers is consistent with previously calculated values and with theory. Cyclone boilers emit a lower proportion of fly ash versus bottom ash than do pulverized coal-fired boilers. The summarized uncontrolled emission factors are presented as a range (from 115 to 310 lb/10^{12} Btu). Assuming an arsenic control efficiency of 87.5 percent for ESPs, the uncontrolled emission factor corresponding to 14.4 lb/10^{12} Btu would be 115 lb/10^{12} Btu; however, limited test data and calculations suggest a slightly higher value. The average uncontrolled factor for one boiler tested is 310 lb/10^{12} Btu. Calculations show a minimum uncontrolled emission factor of 210 lb/10^{12} Btu for cyclone boilers. This calculation assumes arsenic is emitted in the same proportion as total particulates (13.5 percent of total ash is emitted as fly ash (Baig et al., 1981)). It also assumes that the typical arsenic content of bituminous coal is 20.3 ppm, and that the heating value is 13,077 Btu/lb. In reality, arsenic is concentrated in the fly ash, so a somewhat higher emission factor would be expected.

Mechanical precipitators, which reduce arsenic emissions by about 51 percent, would produce emission factors for bituminous coal-fired cyclone boilers of between 56 and 152 lb/10^{12} Btu.

The only value reported for a cyclone boiler controlled by a scrubber (see Table 4-39) is much higher than ESP-controlled or uncontrolled emission factors and is inconsistent with theory. There is not enough information to derive a reliable emission factor for coal-fired cyclone boilers controlled with scrubbers.

Bituminous Coal-Fired Stoker Boilers. The most complete data on stoker boilers are for the industrial sector. Fourteen tests of seven industrial spreader stokers and five tests of four overfeed stokers are summarized in Table 4-42 and in Appendix C, Table C-7. It is uncertain whether these two types of stokers should be combined in determining an average emission factor. The range and average measured emission factors are lower for the spreader stokers than for the overfeed stokers (averages of 264 versus 1,030 lb/10^{12} Btu, respectively). Weighting all eleven boilers equally, regardless of type, the average emission factor of 542 lb/10^{12} Btu can be derived for all industrial stoker boilers.

Summary emission factors for spreader stokers in Table 4-38 are presented as a range, with the average for spreader stokers at the lower end of the range and the average for all stokers at the upper end. One of the utility boilers tested (Table 4-39) falls within this range, the other can be excluded as an outlier. Applying the control percentages in Table 4-46 to either end of this range, the emission factors for spreader stokers controlled with multiclones would range from 129 to 265 lb/10^{12} Btu, and for ESPs would range from 33 to 67 lb/10^{12} Btu. These ranges are in general agreement with the limited test data on controlled spreader stokers presented in Table 4-42.

For uncontrolled overfeed stokers the summarized range of emission factors is 542 lb/10^{12} Btu (the mean for all stokers tested) to 1,030 lb/10^{12} Btu (the mean for overfeed stokers tested). Controlled emission factors, based on the control efficiencies in Table 4-46, would be 265 to 505 lb/10^{12} Btu for multiclone-controlled overfeed stokers and 67 to 129 lb/10^{12} Btu for ESP-controlled overfeed stokers.

Based on limited data, about 60 percent of the total ash from stoker boilers fired with bituminous coal is emitted as fly ash (Baig et al., 1981). The type of stoker is not specified. This would lead to a minimum calculated arsenic emission rate of 930 lb/10^{12} Btu if arsenic were distributed equally between fly ash and bottom ash. This calculation does not account for the enrichment of arsenic on fly ash, which would have the effect of raising the emission factor. It is uncertain why measured emission factors for spreader stokers are generally below this calculated value.

Subbituminous Coal-Fired Boilers. Summary emission factors for subbituminous coal-fired boilers were not calculated. There is a lack of test data, and much of the available information does not distinguish between bituminous and subbituminous coals. Tables 4-40 and 4-43 summarize the data on emission factors for subbituminous coal which are available in the literature.

Lignite Coal-Fired Boilers. The only data on lignite coal-fired boilers are for the utility sector and are presented in Table 4-41 and in Appendix C, Table C-6. Since there are only one or two tests of each boiler type/control device combination, representative emission factors cannot be derived from the test data. The assumption can be made that the main cause of variability between similar boilers firing bituminous and lignite coal would be the different average arsenic content of the two types of coal. Making this assumption, emission factors for lignite combustion can be calculated from the emission factors for bituminous combustion by applying a ratio to account for the higher average arsenic content of lignite coal (22.8 versus 20.3 ppm) and for the difference in heating values (7,194 Btu/lb for lignite versus 13,077 Btu/lb for bituminous). Summary emission factors calculated in this manner are presented in Table 4-38. There are inadequate data to determine whether burning lignite as opposed to bituminous coal results in any differences in the proportion of fly ash to bottom ash generated, or in the characteristics of the fly ash, or trace element enrichment behavior, so these types of considerations were not incorporated into the calculations. As can be seen by comparing the emission factors in Table 4-38 with the test data for lignite combustion summarized in Table 4-41, there is general agreement between the two sets of factors.

Anthracite Coal-Fired Boilers. The only data for anthracite combustion is testing of three commercial/ institutional stoker boilers summarized in Table 4-44. Summary emission factors for anthracite combustion can be calculated from summarized bituminous coal factors by applying a ratio to account for the different arsenic content of the two types of coal (7.67 ppm for anthracite and 20.3 ppm for bituminous) and for the different heat contents (12,700 for anthracite versus 13,077 for bituminous). These calculated values are shown in Table 4-38. The measured arsenic emission factor for uncontrolled stoker boilers (137 lb/10^{12} Btu) is in good agreement with the calculated values for spreader stokers (103-210 lb/10^{12} Btu).

Beryllium Emission Factors-

Table 4-47 presents summary beryllium emission factors for utility, industrial, and commercial/institutional boilers. Where possible, these were derived from emissions test data. The data base is summarized in Tables 4-48 through 4-53. Ranges and average measured emission factors along with the number of boilers tested and the number of test runs are presented for each combination of sector, coal type, boiler design, and control technology. More detailed information on individual tests, including references, is presented in Appendix C (Tables C-11 through C-19).

Bituminous Coal-fired Pulverized Dry Bottom Boilers. The summary emission factor for uncontrolled pulverized dry bottom boilers fired with bituminous coal is 81 lb/10^{12} Btu. As shown on Table 4-48, this is the average of seventeen tests of four utility boilers. This is in agreement with previously calculated values shown in Table 4-54. One industrial and one commercial boiler were also tested. The measured emission factor for the industrial boiler was lower than for any of the utility boilers tested, and the commercial boiler was higher than any of the utility boilers (see Tables 4-51 and 4-53). However, since these are only single data points, it is believed that the summarized average emission factor of 81 lb/10^{12} Btu for utility boilers is more representative of emissions from boilers in all three sectors.

TABLE 4-47. SUMMARIZED BERYLLIUM EMISSION FACTORS FOR COAL-FIRED BOILERS

	Emission Factor ($lb/10^{12}$ Btu) by Coal Type		
Boiler Type/Control Status	Bituminous	Lignite	Anthracite
Pulverized (Dry or Wet Bottom):			
Uncontrolled	81	131	50
Multiclone	52	84	32
ESP	3.0	4.9	1.8
Scrubber	0.11	0.18	0.07
Cyclone Boilers:			
Uncontrolled	<81	<130	<50
Multiclone	<52	<84	<32
ESP	0.52	0.84	0.32
Stoker Boilers:			
Uncontrolled	73	118	45
Multiclone	9.8-46	16-74	6-28
ESP	5.9	9.5	3.6

TABLE 4-48. SUMMARY OF MEASURED BERYLLIUM EMISSION FACTORS FOR BITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu)		Number of Boilers Tested	Number of Data Points
	Average[a]	Range		
Pulverized Dry Bottom:				
Uncontrolled	80.9	41-140	4	17
Mechanical Ppt.	93.5	26-171	2	10
ESP or Mech. Ppt/ESP	3.8	<0.11-32	12	25
Mech. Ppt/2 ESPs in series	0.082	0.007-0.209	1	5
Scrubber	0.11	---	1	1
Pulverized Wet Bottom:				
ESP or Mech. Ppt/ESP	3.5	0.88-10.2	5	5
Scrubber	0.086	---	1	1
Cyclone:				
ESP	0.52	0.19-1.05	4	4
Scrubber	0.86	---	1	1
Stoker:				
Mech. Ppt or Multiclone	12.8	5.6-20.0	2	2
Fabric Filter	0.13	---	1	1

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[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-49. SUMMARY OF MEASURED BERYLLIUM EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Range	Number of Boilers	Number of Data Points
Pulverized Coal Fired:				
ESP	1.0	---	1	1
Scrubber	0.60	---	1	1
Cyclone:				
Uncontrolled	18.0	---	1	1
Scrubber	1.6	---	1	1
Unspecified Boiler Type:				
ESP	0.63	0.38-0.88	2	2

TABLE 4-50. SUMMARY OF MEASURED BERYLLIUM EMISSION FACTORS FOR LIGNITE COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Multiclones	2.4	2.3-2.6	2	2
ESP	<2.3	---	1	1
Cyclone:				
Cyclone	6.8	---	1	1
ESP	0.70	---	1	1
Spreader Stoker:				
Multiclone	13.7	---	1	1
ESP	0.26	---	1	1

TABLE 4-51. SUMMARY OF MEASURED BERYLLIUM EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Uncontrolled	15	---	1	2
Multiclone	93	---	1	1
Multiclone/Scrubber	2.3	---	1	1
ESP	1.1	0.19-2.0	5	6
Pulverized Wet Bottom:				
Multiclone	0.21	---	1	1
Spreader Stoker:				
Uncontrolled	106	0.30-780	7	14
Multiclone	7.7	3.3-12.1	2	2
Multiclone/ESP	32	0.2-120	2	3
Overfeed Stoker:				
Uncontrolled	16.6	3.9-39	4	5
Economizer/Dust Collector	4.3	3.7-4.9	1	2

[a] Each boiler tested was weighted equally in determining this average. An arithmetic value was calculated for each boiler, and then a means of these means was calculated.

TABLE 4-52. SUMMARY OF MEASURED BERYLLIUM EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Range	Number of Boilers	Number of Data Points
Spreader Stoker:				
Uncontrolled	41.3	6.2-70	2	4
Mechanical Ppt/ESP	2.0	0.77-3.3	1	2

[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-53. SUMMARY OF MEASURED BERYLLIUM EMISSION FACTORS FOR COMMERCIAL/INSTITUTIONAL COAL-FIRED BOILERS

Coal Type/ Boiler Type	Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Range	Number of Boilers	Number of Data Points
Bituminous Coal:					
Pulverized Dry Bottom	Uncontrolled	307	---	1	1
	Multiclone/ Scrubber	0.95	---	1	1
Spreader Stoker	Mechanical Ppt	7.9	---	1	1
Overfeed Stoker	Mechanical Ppt	0.77	---	1	1
Anthracite Coal:					
Stoker	Uncontrolled	11.1	0.93-21.8	3	3

TABLE 4-54. CALCULATED BERYLLIUM EMISSION FACTORS FOR COAL COMBUSTION

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor ($lb/10^{12}$ Btu)	Reference
Bituminous	Pulverized Dry Bottom	Uncontrolled	U, I, C	70-90	Baig et al., 1981
Bituminous	Pulverized Dry Bottom	Uncontrolled	I, C	232	Suprenant et al., 1980a; Suprenant et al., 1980b
Bituminous	Pulverized Dry Bottom	Mechanical Ppt.	U, I	72	Shih et al., 1980b; Suprenant et al., 1980b
Bituminous	Pulverized Dry Bottom	ESP	U, I	5.1	Baig et al., 1981; Shih et al., 1980b
Bituminous	Pulverized Dry Bottom	Wet Scrubber	U	0.42	Shih et al., 1980b
Bituminous	Pulverized Wet Bottom	Uncontrolled	U, I	58-90	Baig et al., 1981
Bituminous	Pulverized Wet Bottom	Mechanical Ppt.	U	58	Shih et al., 1980b
Bituminous	Pulverized Wet Bottom	Multiclone	U, I	17	Baig et al., 1981
Bituminous	Pulverized Wet Bottom	ESP	U	4.2	Baig et al., 1981; Shih et al., 1980b
Bituminous	Pulverized Wet Bottom	Wet Scrubber	U	0.42	Shih et al., 1980b
Bituminous	Cyclone	Uncontrolled	U	12-88	Baig et al., 1981
Bituminous	Cyclone	Mechanical Ppt.	U	12	Shih et al., 1980b
Bituminous	Cyclone	ESP	U	0.86	Shih et al., 1980b; Baig et al., 1981
Bituminous	Cyclone	Wet Scrubber	U	0.07	Shih et al., 1980b

TABLE 4-54. CALCULATED BERYLLIUM EMISSION FACTORS FOR COAL COMBUSTION (Continued)

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor ($lb/10^{12}$ Btu)	Reference
Bituminous	Stoker	Uncontrolled	U, I, C	53-88	Baig et al., 1981
Bituminous	Stoker	Multiclone	U, I, C	16	Baig et al., 1981
Bituminous	Spreader Stoker	Uncontrolled	I	179	Suprenant et al., 1980a
Bituminous	Spreader Stoker	Cyclone	I	56	Suprenant et al., 1980a
Bituminous	Underfeed Stoker	Uncontrolled	C	23	Suprenant et al., 1980b
Bituminous	Automatic Coal-Fired Furnance	Uncontrolled	R	16	DeAngelis and Reznik, 1979
Lignite	Pulverized Dry Bottom	Uncontrolled	U, I, C	51-150	Baig et al., 1981
Lignite	Pulverized Dry Bottom	Multiclone	U, I, C	14	Baig et al., 1981
Lignite	Pulverized Dry Bottom	Mechanical Ppt.	U	37	Shih et al., 1980b
Lignite	Pulverized Dry Bottom	ESP	U	1.4	Shih et al., 1980b
Lignite	Pulverized Dry Bottom	Wet Scrubber	U	0.63	Shih et al., 1980b
Lignite	Cyclone	Uncontrolled	U	44-150	Baig et al., 1981
Lignite	Cyclone	Mechanical Ppt.	U	35	Shih et al., 1980b
Lignite	Cyclone	ESP	U	0.72	Shih et al., 1980b
Lignite	Cyclone	Wet Scrubber	U	0.33	Shih et al., 1980b
Lignite	Stoker	Uncontrolled	U, I, C	51-150	Baig et al., 1981

TABLE 4-54. CALCULATED BERYLLIUM EMISSION FACTORS FOR COAL COMBUSTION (Continued)

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor (lb/10^{12} Btu)	Reference
Lignite	Stoker	Multiclone	U, I, C	14	Baig et al., 1981
Lignite	Automatic Coal-Fired	Uncontrolled	R	2.8	DeAngelis and Reznik, 1979
Anthracite	Pulverized Dry Bottom	Uncontrolled	U, I, C	74-88	Baig et al., 1981
Anthracite	Stoker	Uncontrolled	U, I, C	4.4-88	Baig et al., 1981
Anthracite	Stoker	Uncontrolled	C	16	Suprenant et al., 1980b
Anthracite	Automatic Coal-Fired Furnance	Uncontrolled	R	16	DeAngelis and Reznik, 1979

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

There are insufficient data to derive a meaningful average emission factor for multiclone-controlled pulverized dry bottom boilers. Although the coals for the two utility boilers tested contained the same amount of beryllium (1.4 to 1.7 ppm for both boilers), emission factors for one boiler averaged 52 lb/10^{12} Btu, and for the other boiler averaged 154 lb/10^{12} Btu. A summary emission factor of 51 lb/10^{12} Btu was calculated by applying a control efficiency of 37 percent to the uncontrolled emission factor of 81 lb/10^{12} Btu. This control efficiency is specific to beryllium, and was determined from tests of control device efficiency found in the data base (see Table 4-55).

The summary emission factor for ESP-controlled pulverized dry bottom boilers is 3.0 lb/10^{12} Btu. This is an average of tests of 12 utility boilers and five industrial boilers, with each boiler weighted equally. Only one boiler with a scrubber was tested and it was found to emit 0.11 lb/10^{12} Btu (see Table 4-48).

Bituminous Coal-Fired Pulverized Wet Bottom Boilers. Tests of five ESP-controlled pulverized wet bottom boilers yielded an average emission factor of 3.5 lb/10^{12} Btu (Table 4-48). Data are lacking on uncontrolled wet bottom boilers and wet bottom boilers controlled by other technologies.

Bituminous Coal-Fired Cyclone Boilers. The average measured emission factor for four cyclone boilers controlled with ESPs is 0.52 lb/10^{12} Btu (Table 3-106). The lower emission factor for cyclone boilers in contrast to pulverized coal-fired boilers is consistent with previously calculated emission factors and may be explained by the fact that cyclone boilers emit less fly ash than pulverized coal-fired boilers (Baig et al., 1981).

There are no emissions tests of uncontrolled cyclone boilers or of multiclone-controlled cyclone boilers in the literature. The emission factors for pulverized coal-fired boilers may be used as an upper estimate of beryllium emissions from cyclone boilers. In reality, emissions may be somewhat lower because less fly ash is emitted, but the volatilization/condensation behavior of beryllium has not been well enough characterized to calculate a precise emission factor for cyclone boilers.

TABLE 4-55. BERYLLIUM REMOVAL EFFICIENCY OF CONTROLS[a]

Control Device	% Control Efficiency Average[b]	 Range	Number of Boilers	Number of Test Runs
Mechanical Ppt.	37.0	34.6-40.9	1	3
ESP	82.4[c] 91.9[d]	22.0-99.95[b] 86.7-99.95[c]	6[b] 5[c]	19[b] 16[c]
FGD Scrubber	94.3	91.1-97.5	2	2
2 ESPs in Series	99.94	99.91-99.995	1	5

[a] These control efficiencies represent measured control levels reported in the literature. They may or may not be indicative of the long-term performance of these types of controls on beryllium emissions from combustion sources. The average values should not be construed to represent an EPA-recommended efficiency level for these devices.

[b] Each emission test weighted equally.

[c] Average and range represent data from all six ESP-controlled boilers in the data set for which controlled and uncontrolled data are available.

[d] Average and range represent data for five out of six ESP-controlled boilers in the data set. The other boiler was excluded as an outlier. Control efficiency for the outlier was 34.4 percent, while for the other five boilers, control efficiencies were over 86 percent.

Bituminous Coal-Fired Stoker Boilers. Several tests of industrial boilers (summarized in Table 4-51) were used to characterize bituminous coal-fired stoker boiler emissions. For eleven uncontrolled stoker boilers (four overfeed and seven spreader stokers), the average beryllium emission factor, weighting each boiler equally, is 73 lb/10^{12} Btu. Two utility, two industrial, and one commercial spreader stoker controlled with multiclones were tested (see Tables 4-48, 4-51, and 4-53). The average emission factor for these five boilers is 9.8 lb/10^{12} Btu. This is lower than the value of 46 lb/10^{12} Btu which may be calculated by applying a beryllium control efficiency of 37 percent (see Table 4-55) to the summary uncontrolled emission factor for stoker boilers. The summarized emission factor for multiclone-controlled stokers is therefore presented as a range, from 9.8 to 46 lb/10^{12} Btu.

Assuming a control efficiency of 91.9 percent (Table 4-55), the emission factor for ESP-controlled stokers would be 5.9 lb/10^{12} Btu.

Subbituminous Coal-Fired Boilers. Much of the literature does not distinguish between bituminous and subbituminous coals. Due to a lack of data, emission factors specific to subbituminous coal are not presented. Measured emission factors for subbituminous coal combustion available in the literature are summarized in Tables 4-49 and 4-52, and in Appendix C.

Lignite and Anthracite Coal-Fired Boilers. Data on lignite-fired boilers are limited. Table 4-49 summarizes the measured emission factors found in the literature. The only measured emission factors available for anthracite coal are from tests of three commercial/institutional stokers. These are summarized in Table 4-52.

Due to the lack of data, beryllium emission factors for lignite and anthracite coal were calculated from the summary factors for bituminous coal. These were proportioned to account for the differences in beryllium content and heating values of the three coals. From Table 3-8, the average beryllium content of bituminous coal is 2.22 ppm, the average beryllium content of lignite is 1.98 ppm, and that of anthracite is 1.32 ppm. Heating values for the three coals are 13,077 Btu/lb for bituminous, 7,194 for lignite, and 12,700 for anthracite. The factors determined by this procedure are given in Table 4-47. Emission factors calculated for lignite are somewhat higher than bituminous coal emission factors, and emission factors for anthracite are lower.

Cadmium Emission Factors-

Table 4-56 contains typical cadmium emission factors for utility, industrial, and commercial/institutional combustion sectors derived from data available in the literature. The data base is summarized in Tables 4-57 through 4-62. For each sector/coal type/boiler design/control device combination, the number of boilers tested, the number of test runs made, and the average and range of emission factors measured are reported. A summary of each test, including references, is contained in Appendix C, Tables C-20 through C-29.

Bituminous Coal-Fired Pulverized Dry Bottom Boilers. Pulverized dry bottom boilers in the utility, industrial, and commercial/institutional sectors have been tested. Results are summarized in Tables 4-57, 4-60, and 4-62. The results of the industrial boiler test were excluded because the mass balance suggested more cadmium being emitted than was input to the boiler. Testing of five uncontrolled utility boilers yielded an average cadmium emission factor of 44.4 lb/10^{12} Btu. This is in agreement with previously calculated values shown in Table 4-63. Using the average cadmium content of bituminous coal (0.91 ppm), the predicted cadmium emissions would be between 55 and 70 lb/10^{12} Btu. The lower value assumes 80 percent of the total ash generated is emitted as fly ash (Baig et al., 1981) and that cadmium is emitted in the same proportion as total particulates. The upper value assumes all cadmium present in the coal feed is emitted. Since cadmium is enriched in the fly ash, the actual value should be between the two. Since calculated and measured values are in close agreement, the measured value (44.4 lb/10^{12} Btu) may be viewed as a typical cadmium emission factor for uncontrolled pulverized dry bottom boilers. However, as noted in Section 3, some coals from the Interior region have much higher than average cadmium contents, which would result in higher cadmium emissions.

TABLE 4-56. SUMMARIZED CADMIUM EMISSION FACTORS FOR COAL-FIRED BOILERS

	Emission Factor (lb/10^{12} Btu) by Coal Type		
Boiler Type/Control Status	Bituminous	Lignite	Anthracite
Pulverized Dry Bottom:			
Uncontrolled	44.4	48.8	11
Multiclone	31.6	34.8	7.9
ESP	9.2 (5.0-20)[a]	10 (5.5-22)	2.3 (1.2-5.0)
Scrubber	0.35-1.6	0.38-1.8	0.09-0.40
Pulverized Wet Bottom:			
Uncontrolled	45-70	49-77	11-17
Multiclone	32-50	35-55	8.0-12
ESP	1.4	1.5	0.35
Cyclone:			
Uncontrolled	28	31	7.0
Multiclone	20	22	5.0
ESP	1.3	1.4	0.32
Spreader Stoker:			
Uncontrolled	21-43	23-47	5.2-11
Multiclone	6.6-30	7.3-33	1.6-7.5
ESP	5.3-11	5.8-12	1.3-2.7
Overfeed Stoker:			
Uncontrolled	43-82	47-90	11-20
Multiclone	30-58	33-64	7.5-14
ESP	11-21	12-23	2.7-5.2

[a] 9.2 is the average bituminous coal emission factor for all boilers tested. The lower end of the given range is the average factor for 13 utility boilers tested, and the upper end is the average of 5 industrial boilers tested.

TABLE 4-57. SUMMARY OF MEASURED CADMIUM EMISSION FACTORS FOR BITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Number of Boilers Tested	Number of Data Points
Pulverized Dry Bottom:				
Uncontrolled	44.4	9.2-167	5	17
Mechanical Ppt.	161	15-487	2	10
ESP or Mech. Ppt/ESP	5.0	0.22-52.8	13	26
2 ESPs in Series	46	---	1	1
Scrubber	1.6	1.2-1.95	2	2
Pulverized Wet Bottom:				
ESP or Mech. Ppt/ESP	1.4	0.56-2.6	5	5
Scrubber	0.086	---	1	1
Cyclone:				
Uncontrolled	28	22-35	1	2
ESP	1.3	0.35-3.0	5	6
Wet Scrubber	488	---	1	1
Stoker:				
Mechanical Ppt. or Multiclone	13.2	4.2-22.1	2	2
Fabric Filter	0.33	---	1	1

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[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-58. SUMMARY OF MEASURED CADMIUM EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Range	Number of Boilers	Number of Data Points
Pulverized Coal Fired:				
ESP	<0.40	---	1	1
Scrubber	4.0	---	1	1
Cyclone:				
Uncontrolled	4400	---	1	1
Scrubber	490	---	1	1
Unspecified Boiler Type:				
ESP	1.04	0.39-1.7	2	2

TABLE 4-59. SUMMARY OF MEASURED CADMIUM EMISSION FACTORS FOR LIGNITE COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Multiclone	15.4	5.1-25.6	2	2
ESP	<3.5	---	1	1
Cyclone Boilers:				
Cyclone	16	---	1	1
ESP	1.2	---	1	1
ESP/Scrubber	30.6	1.8-59	1	2
Spreader Stoker:				
Multiclone	5.3	---	1	1
ESP	1.9	---	1	1

TABLE 4-60. SUMMARY OF MEASURED CADMIUM EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Uncontrolled	290	---	1	1
Multiclone	465	---	1	1
ESP	20	0.49-39	5	5
Multiclone/Scrubber	0.98	---	1	1
Pulverized Wet Bottom:				
Multiclone	1.5	---	1	1
Spreader Stoker:				
Uncontrolled	21	4.1-65	7	14
Multiclone	0.56	0.19-0.93	2	2
ESP	1.36	0.009-4.2	2	3
Overfeed Stoker:				
Uncontrolled	82	12-300	4	5
Economizer/Dust Collector	56	44-67	1	2

[a] Each boiler was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-61. SUMMARY OF MEASURED CADMIUM EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Range	Number of Boilers	Number of Data Points
Spreader Stoker:				
Uncontrolled	99	4.9-290	2	4
Mechanical Ppt/ESP	9.8	5.7-14	1	2

[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-62. SUMMARY OF MEASURED CADMIUM EMISSION FACTORS FOR COMMERCIAL/INSTITUTIONAL COAL-FIRED BOILERS

Coal Type/ Boiler Type	Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Emission Factor ($lb/10^{12}$ Btu) Range	Number of Boilers	Number of Data Points
Bituminous Coal:					
Pulverized Dry Bottom	Uncontrolled	12.8	---	1	1
	Multiclone/Scrubber	0.35	---	1	1
Spreader Stoker	Mechanical Ppt.	5.6	---	1	1
Overfeed Stoker	Mechanical Ppt.	1.2	---	1	1
Anthracite Coal:					
Stoker	Uncontrolled	2.4	1.4-3.5	3	3

TABLE 4-63. CALCULATED CADMIUM EMISSION FACTORS FOR COAL COMBUSTION

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor ($lb/10^{12}$ Btu)	Reference
Bituminous	Pulverized Dry Bottom	Uncontrolled	U, I, C	49-60	Baig et al., 1981
Bituminous	Pulverized Dry Bottom	Uncontrolled	I, C	186	Suprenant et al., 1980a; Suprenant et al., 1980b
Bituminous	Pulverized Dry Bottom	Mechanical Ppt.	U, I	56	Shih et al., 1980b; Suprenant et al., 1980a
Bituminous	Pulverized Dry Bottom	ESP	U, I	3.9	Baig et al., 1981; Shih et al., 1980b
Bituminous	Pulverized Dry Bottom	Wet Scrubber	U	6.5	Shih et al., 1980b
Bituminous	Pulverized Wet Bottom	Uncontrolled	U, I	39-60	Baig et al., 1981
Bituminous	Pulverized Wet Bottom	Mechanical Ppt.	U	44.2	Shih et al., 1980b
Bituminous	Pulverized Wet Bottom	Multiclone	U, I	12	Baig et al., 1981
Bituminous	Pulverized Wet Bottom	ESP	U, I	3.2	Baig et al., 1981; Shih et al., 1980b
Bituminous	Pulverized Wet Bottom	Wet Scrubber	U	6.0	Shih et al., 1980b
Bituminous	Cyclone	Uncontrolled	U	8.1-60	Baig et al., 1981
Bituminous	Cyclone	Mechanical Ppt.	U	9.3	Shih et al., 1980b
Bituminous	Cyclone	ESP	U	0.67	Baig et al., 1981; Shih et al., 1980b
Bituminous	Cyclone	Wet Scrubber	U	1.1	Shih et al., 1980b

TABLE 4-63. CALCULATED CADMIUM EMISSION FACTORS FOR COAL COMBUSTION (Continued)

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor ($lb/10^{12}$ Btu)	Reference
Bituminous	Stoker	Uncontrolled	U, I, C	37-60	Baig *et al.*, 1981
Bituminous	Stoker	Multiclone	U, I, C	11	Baig *et al.*, 1981
Bituminous	Spreader Stoker	Uncontrolled	I	142	Suprenant *et al.*, 1980a
Bituminous	Spreader Stoker	Cyclone	I	42	Suprenant *et al.*, 1980a
Bituminous	Underfeed Stoker	Uncontrolled	C	23	Suprenant *et al.*, 1980a
Bituminous	Automatic Coal-Fired Furnace	Uncontrolled	R	39	DeAngelis and Reznik, 1979
Lignite	Pulverized Dry Bottom	Uncontrolled	U, I, C	15-42	Baig *et al.*, 1981
Lignite	Pulverized Dry Bottom	Multiclone	U, I, C	3.9	Baig *et al.*, 1981
Lignite	Pulverized Dry Bottom	Mechanical Ppt.	U	14	Shih *et al.*, 1980b
Lignite	Pulverized Dry Bottom	ESP	U	0.49	Shih *et al.*, 1980b
Lignite	Pulverized Dry Bottom	Wet Scrubber	U	4.2	Shih *et al.*, 1980b
Lignite	Cyclone	Uncontrolled	U	12-42	Baig *et al.*, 1981
Lignite	Cyclone	Mechanical Ppt.	U	14	Shih *et al.*, 1980b
Lignite	Cyclone	ESP	U	0.28	Shih *et al.*, 1980b
Lignite	Cyclone	Wet Scrubber	U	2.3	Shih *et al.*, 1980b
Lignite	Stoker	Uncontrolled	U, I, C	15-42	Baig *et al.*, 1981

TABLE 4-63. CALCULATED CADMIUM EMISSION FACTORS FOR COAL COMBUSTION (Continued)

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor ($lb/10^{12}$ Btu)	Reference
Lignite	Stoker	Multiclone	U, I, C	3.9	Baig *et al.*, 1981
Lignite	Automatic Coal-Fired Furnace	Uncontrolled	R	11	DeAngelis and Reznik, 1979
Anthracite	Pulverized Dry Bottom	Uncontrolled	U, I, C	11-13	Baig *et al.*, 1981
Anthracite	Stoker	Uncontrolled	U, I, C	0.65-13	Baig *et al.*, 1981
Anthracite	Stoker	Uncontrolled	C	2.3	Suprenant *et al.*, 1980b
Anthracite	Automatic Coal-Fired Furnace	Uncontrolled	R	16	DeAngelis and Reznik, 1979

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

Only three sources with multiclones were tested, one of which had relatively low emissions, while the other two had extremely high emissions. A meaningful average cannot be derived from these tests. The summarized emission factor shown on Table 4-56 was derived from the uncontrolled emission factor (44.4 lb/10^{12} Btu) by assuming multiclones are 28.9 percent efficient for cadmium control. This efficiency for cadmium was derived from test data at the inlet and outlet of a multiclone applied to a combustion source (see Table 4-64). The multiclone-controlled emission factor calculated by this method is 31.6 lb/10^{12} Btu.

The ranges of measured cadmium emission factors for utility and industrial pulverized dry bottom boilers were similar, but the average for industrial boilers was somewhat higher. The data are summarized in Tables 4-57 and 4-60. The cadmium control efficiencies for the ESPs in the data base also varied greatly (see Table 4-64). For this reason, the summary emission factor is expressed as a range, with the average utility boiler emission factor (5.0 lb/10^{12} Btu) being the low end of the range and the average industrial boiler factor (20 lb/10^{12} Btu) being the high end. An average of all 18 utility and industrial boilers yields a cadmium emission factor of 9.2 lb/10^{12} Btu.

A utility boiler and a commercial/institutional boiler, both controlled with scrubbers, were tested and found to have cadmium emissions of 1.6 and 0.35 lb/10^{12} Btu, respectively. These measurements were used to derive the range of summarized cadmium factors shown in Table 4-56.

Bituminous Coal-Fired Pulverized Wet Bottom Boilers. Based on tests of five boilers, ESP-controlled wet bottom boilers may emit less cadmium than ESP-controlled dry bottom boilers as shown in Table 4-57. The cadmium contents of the coals burned during these tests were not reported. Based on these tests, the summary emission factor for ESP-controlled pulverized wet bottom boilers is 1.4 lb/10^{12} Btu.

Since no tests of uncontrolled or multiclone-controlled wet bottom boilers were reported in the literature, emission factors were calculated based on cadmium levels in coal. Based on an average cadmium content of 0.91 ppm for bituminous coal, uncontrolled cadmium emissions would range

TABLE 4-64. CADMIUM REMOVAL EFFICIENCY OF CONTROLS[a]

Control Device	Percent Control Average[b]	Percent Control Range	Number of Boilers	Number of Data Points
ESP	74.6	18.3-99.7	8	21
Mechanical Ppt.	28.9	24.3-37.5	1	3
ESP/Scrubber	>67	>54->67	1	2
2 ESPs in Series	90.5	---	1	1
Scrubber	94.4	88.9-99.8	2	2

[a] These control efficiencies represent measured control levels reported in the literature. They may or may not be indicative of the long-term performance of these types of controls on cadmium emissions from combustion sources. The average values should not be construed to represent an EPA-recommended efficiency level for these devices.

[b] Each emission test weighted equally.

from 45 to 70 lb/10^{12} Btu. The lower end of this range assumes that 65 percent of total ash is emitted as fly ash (Baig et al., 1981) and that cadmium is emitted in the same proportion as total particulates. The upper end of the range assumes all cadmium present in the coal feed is emitted. Since cadmium is preferentially concentrated in the fly ash, the actual value should be between these two.

The range of emission factors for multiclone-controlled boilers is derived from the uncontrolled emission factors by assuming 28.9 percent cadmium control (see Table 4-64).

Bituminous Coal-Fired Cyclone Boilers. Based on the testing of five sources, average cadmium emissions for bituminous coal-fired cyclone boilers controlled by ESPs are estimated to be 1.3 lb/10^{12} Btu. The lower cadmium emissions for cyclone boilers versus pulverized coal-fired boilers may be due to the fact that less fly ash is emitted from cyclone boilers (Baig et al., 1981).

The only uncontrolled boiler tested emitted 28 lb/10^{12} Btu. This is the summarized emission factor shown in Table 4-56. It is supported by calculations. Calculated values, which range from a minimum of 9.4 to a maximum of 70 lb/10^{12} Btu, support this value. The minimum factor is calculated assuming cadmium is emitted in the same proportion as total particulates and that 13.5 percent of the total ash is emitted as fly ash (Baig et al, 1981). The maximum value is calculated assuming all cadmium in the coal is emitted. The actual value should fall between these two extremes.

Assuming multiclones have a cadmium removal efficiency of 28.9 percent (Table 4-64), the average emission factor of 20 lb/10^{12} Btu can be derived for cyclone boilers controlled with multiclones.

Bituminous Coal-Fired Stoker Boilers. Test results for eleven uncontrolled industrial stoker boilers were identified. Although the ranges of measured emission factors overlap, the average cadmium emission factor for the overfeed stokers was higher than the average for spreader stokers (see Table 4-60). The combined average for all eleven stokers (both spreader and overfeed) is 43 lb/10^{12} Btu. Summarized typical emission factors are presented as a range. For spreader stokers, the range is from 21 lb/10^{12} Btu (the average for seven spreader stokers tested) to 43 lb/10^{12} Btu (the average for all stokers). For overfeed stokers the range is 43 lb/10^{12} Btu to 82 lb/10^{12} Btu (82 lb/10^{12} Btu is the average emission factor for the four overfeed stokers tested). The average emission factor for multiclone-controlled spreader stokers is 6.6 lb/10^{12} Btu based on tests of two utility boilers, two industrial boilers, and one commercial boiler. This factor is somewhat lower than expected. Based on average uncontrolled emissions of 21 lb/10^{12} Btu and a control efficiency of 28.9 percent for multiclones (Table 4-64), the calculated emission factor would be between 15 and 30 lb/10^{12} Btu. The summary emission factor is, therefore, presented as a range from 6.6 to 30 lb/10^{12} Btu.

There is a lack of test data on multiclone-controlled overfeed stokers. Based on uncontrolled emission factors and 28.9 percent cadmium control, the range of cadmium emission factors for multiclone-controlled overfeed stokers would be 30 to 58 lb/10^{12} Btu.

Assuming ESPs result in 74.6 percent cadmium emissions control (see Table 4-64), typical cadmium emission factors for ESP-controlled spreader stokers would range from 5.3 to 11 lb/10^{12} Btu. This is in agreement with the measured emission factor for an ESP-controlled spreader stoker fired with subbituminous coal shown in Table 4-61. The calculated emission factor for overfeed stokers controlled with ESPs ranges from 11 to 21 lb/10^{12} Btu.

Subbituminous Coal-Fired Boilers. The available emission factor data for subbituminous coal-fired boilers are presented in Tables 4-58 and 4-61. There are insufficient data to derive summary emission factors. In the literature, subbituminous coal often is not differentiated from bituminous coal. As discussed in Section 3, the average cadmium content of subbituminous coal is less than the average cadmium content of bituminous coals, so emission factors for subbituminous coal combustion would generally be expected to be below the emission factors for bituminous coal. The coal feed for the utility cyclone boiler test summarized in Table 4-58 had an abnormally high cadmium level (24 ppm versus an average of 0.38 ppm) which may account for the large measured cadmium emission factors.

Lignite and Anthracite Coal-Fired Boilers. All available cadmium test data for lignite coal-fired boilers are summarized in Table 4-59. The available data for anthracite coal-fired boilers are presented in Table 4-62. Since there are not enough measured data to characterize emissions from lignite and anthracite combustion, typical emission factors are calculated from the summary bituminous coal emission factors. For these calculations, it is assumed that for similar boiler designs and control techniques, the main difference in emissions is due to the cadmium content of the three types of coal. Based on typical cadmium contents of the three coals shown in Table 3-13 and heating values in Appendix B, cadmium emission factors for lignite coals would be higher than those for bituminous coal by a factor of 1.10. Anthracite coal emission factors would be lower by a factor of 0.249. The calculated summary emission factors for anthracite and lignite coals are presented in Table 4-56. The measured cadmium emission factors for lignite-fired boilers shown in Table 4-59 are generally similar to the calculated emission factors.

Chromium Emission Factors-

Table 4-65 shows chromium emission factors for boilers in the utility, industrial, and commercial/institutional sectors. These values are calculated from the average chromium content of bituminous, lignite, and anthracite coal. Maximum and minimum uncontrolled emission factors are calculated using the equations:

$$EF_{max} = C/H \times 10^6\text{, and}$$
$$EF_{min} = (C/H)(f) \times 10^6\text{,}$$

Where:
EF = emission factor (lb/10^{12} Btu)
C = concentration of chromium in coal (ppm)
H = heating value of coal (Btu/lb)
f = fraction of coal ash emitted as fly ash

TABLE 4-65. SUMMARIZED CHROMIUM EMISSION FACTORS FOR COAL-FIRED BOILERS

Boiler Type/Control Status	Emission Factor ($lb/10^{12}$ Btu) by Coal Type Bituminous	Lignite	Anthracite
Pulverized Dry Bottom:			
Uncontrolled	1250-1570	1500-1880	2970-3720
Multiclone	721-906	866-1080	1710-2150
ESP	356-447	428-536	846-1060
Scrubber	102-129	123-154	244-305
Fabric Filter	0.0034[a]		
Pulverized Wet Bottom:			
Uncontrolled	1020-1570	1220-1880	2420-3720
Multiclone	588-906	704-1080	1400-2150
ESP	291-447	348-536	690-1060
Scrubber	84-129	100-154	198-305
Cyclone:			
Uncontrolled	212-1570	253-1880	502-3720
Multiclone	122-906	146-1080	290-2150
ESP	60-447	72-536	143-1060
Scrubber	17-129	21-154	41-305
Stoker:			
Uncontrolled	942-1570	1130-1880	2230-3720
Multiclone	544-906	767-1080	1290-2150
ESP	268-447	379-536	636-1060
2 Mechanical Ppt in series	1.5-5.5[b]		

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[a] This value is for hexavalent chromium (Cr^{+6}) and is applicable to utility boilers.

[b] These values are for hexavalent chromium (Cr^{+6}) and are applicable to industrial and commercial boilers.

The minimum value assumes that chromium is emitted in the same proportion as total particulates. The maximum emission factor assumes all chromium in the coal feed is emitted. The values substituted into the equations are shown in Tables 4-66 and 4-67. As described in Section 3, some studies have shown enrichment of chromium in the fly ash. If this occurs, the actual emission factor would be between the minimum and maximum calculated values. Observed enrichment behavior varies between studies and may be a function of coal type, boiler design, and control technology. In general, there are not enough data to develop reliable quantitative enrichment ratios. Therefore, chromium emission factors cannot be calculated precisely and are expressed as a range.

Controlled emission factors are calculated from the uncontrolled emission factors using the control percentages in Table 4-68. These were derived from measurements of control device efficiency for chromium reported in the literature reviewed. Tests where the mass balance around the control device was clearly in error were excluded from the calculations of typical chromium control efficiencies. The efficiencies shown in Table 4-68 may be biased low due to contamination from sampling equipment corrosion. Emission factors calculated using these efficiencies probably represent, in most cases, upper bound estimates.

Measured chromium emission factors are summarized in Tables 4-69 through 4-74 and in Appendix C (Tables C-30 through C-39). In general, the measured values are much higher than the maximum calculated values. The discrepancy is probably due to corrosion of the sampling train components, which would result in artificially high measured chromium emission factors (Baig et al., 1981). Similarly, control device efficiencies for chromium would be artificially reduced below what might actually be occurring.

For all boilers where chromium content of the coal was reported, the coal contained between 10 and 40 ppm chromium, with most tests being near the average value for bituminous coal (20.5 ppm). Therefore, high measured chromium emission factors were not caused by the combustion of high-chromium coals. Some references do not contain enough information to perform mass balance calculations; however, mass balances for several of the boilers indicate more chromium being emitted than was present in the coal feed. Corrosion of sampling train components would explain these results.

TABLE 4-66. VALUES USED IN CALCULATION OF UNCONTROLLED CHROMIUM EMISSION FACTORS

Coal Type	Concentration of Chromium in Coal, ppm (C)[a]	Heating Value, Btu/lb (H)[b]
Bituminous	20.5	13,077
Lignite	13.5	7,194
Anthracite	47.2	12,700

[a] Source: Table 3-19.

[b] Source: Appendix B.

TABLE 4-67. FRACTION OF COAL ASH EMITTED AS FLY ASH (F) BY BOILER TYPE

Boiler Type	Percent Fly Ash (F)[a]
Pulverized Dry Bottom	80
Pulverized Wet Bottom	65
Cyclone	13.5
Stoker	60

[a] These factors are derived from studies of large and intermediate size bituminous coal-fired boilers (Baig et al., 1981; Shih et al., 1980b).

TABLE 4-68. CHROMIUM REMOVAL EFFICIENCY OF CONTROLS[a]

Control Device	Percent Control Average[b]	 Range	Number of Boilers	Number of Data Points
Mechanical Ppt.	42.3	38.9-49.0	1	3
ESP or Mech. Ppt/ESP	71.5	46.7-98.6	5	9
2 ESPs in Series	93.7	82.4-99.4	1	4
ESP/Scrubber	92.9	---	1	1
Scrubber	91.8	90.0-95.2	2	3
2 Multicyclones in series	50.0[c]	___	1	3
Fabric Filter	99.1[c]	___	1	3

[a] These control efficiencies represent measured control levels reported in the literature. They may or may not be indicative of the long-term performance of these types of controls on chromium emissions from combustion sources. Although it can not be unequivocally determined with the available data, these control device efficiencies may be biased low due to contamination from sampling equipment. Emission factors calculated using these efficiencies probably represent, in most cases, upper bound estimates. The average values should not be construed to represent an EPA-recommended efficiency level for these devices.

[b] Each emission test weighted equally in determining average.

[c] These control efficiencies are for hexavalent chromium (Cr^{+6}); the remaining values are for total chromium.

TABLE 4-69. SUMMARY OF MEASURED CHROMIUM EMISSION FACTORS FOR BITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Uncontrolled	1880	244-7900	4	11
Mechanical Ppt.	8980	510-29,700	2	10
ESP or Mech. Ppt/ESP	2860	1.6-7970	12	20
2 ESPs in Series	740	<74-1740	1	4
Scrubber	21.3	4.5-290	3	5
ESP/Scrubber	17.3	---	1	1
Fabric Filter	0.0034[b]	---	1	3
Pulverized Wet Bottom:				
ESP or Mech. Ppt/ESP	1770	86-3320	5	5
Scrubber	0.60	---	1	1
Cyclone:				
Uncontrolled	1150	1000-1300	1	2
ESP	1810	18-5340	5	6
Scrubber	107	---	1	1
Stoker:				
Mech. Ppt or Multiclone	1440	455-2420	2	2
Fabric Filter	153	---	1	1

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[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

[b] This factor is for hexavalent chromium (Cr^{+6}). The average factor was reported in the reference, but the range of values was not.

TABLE 4-70. SUMMARY OF MEASURED CHROMIUM EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Number of Boilers	Number of Data Points
Pulverized Coal Fired:				
ESP	140	---	1	1
Scrubber	390	---	1	1
Cyclone:				
Uncontrolled	1100	---	1	1
Scrubber	100	---	1	1
Unspecified Boiler Type:				
ESP	18.4	8.8-28	2	2

[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-71. SUMMARY OF MEASURED CHROMIUM EMISSION FACTORS FOR LIGNITE COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Multiclone	70.9	67.4-74.4	2	2
ESP	20.0	---	1	1
Cyclone Boiler:				
Cyclone	1000	---	1	1
ESP	<7.7	---	1	1
ESP/Scrubber	4.6	3.1-5.9	1	2
Spreader Stoker:				
Multiclone	30.2	---	1	1
ESP	<5.3	---	1	1

TABLE 4-72. SUMMARY OF MEASURED CHROMIUM EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Multiclone	2,560	---	1	1
ESP	1,130	5.8-1,500	4	4
Multiclone/Scrubber	126	---	1	1
Pulverized Wet Bottom:				
Multiclone	12.3	---	1	1
Spreader Stoker:				
Uncontrolled	3,880	30-8,400	7	13
Multiclone	194	62-325	2	2
Multiclone/ESP	16.6	16-17.2	2	2
2 Mechanical Collectors in series	1.5[b]	—	1	3
Overfeed Stoker:				
Uncontrolled	9,380	1,400-49,000	4	5
Economizer/Dust Collector	15,400	8,800-22,000	1	2

[a] Each boiler was weighted equally in determining the average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

[b] This factor is for hexavalent chromium (Cr^{+6}). The average emission factor was given in the reference, but the range of values was not.

TABLE 4-73. SUMMARY OF CHROMIUM EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^6$ Btu) Average[a]	Emission Factor ($lb/10^6$ Btu) Range	Number of Boilers	Number of Data Points
Spreader Stoker:				
Uncontrolled	1750	280-3500	2	4
Mechanical Ppt/ESP	68	15-120	2	2

[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-74. SUMMARY OF MEASURED CHROMIUM EMISSION FACTORS FOR COMMERCIAL/INSTITUTIONAL COAL-FIRED BOILERS

Coal Type/ Boiler Type	Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Emission Factor ($lb/10^{12}$ Btu) Range	Number of Boilers	Number of Data Points
Bituminous Coal:					
Pulverized Dry Bottom	Uncontrolled	1920	---	1	1
	Multiclone/Scrubber	18.1	---	1	1
Underfeed Stoker	Uncontrolled	18.8	---	1	1
Spreader Stoker	Mechanical Ppt.	100	---	1	1
Overfeed Stoker	Mechanical Ppt.	1840	---	1	1
Anthracite Coal:					
Stoker	Uncontrolled	875	240-1510	3	3

A few emission factors were available for estimating the emissions of hexavalent chromium from coal-fired boilers. The data were based on test results of a pulverized coal boiler (fabric filter control) and a spreader-stoker boiler controlled by two mechanical collectors in series (Ajax and Cuffe, 1985). For utility boilers and industrial boilers, the measured emission factors were used (Tables 4-65, 4-68, 4-69, 4-72, and 4-75). For commercial boilers, the ratio of hexavalent chromium to total chromium emissions (obtained from the test results) was applied to an existing total chromium emission factor. These emission factors represent a limited number of actual data points, but are presented to provide the most data possible.

Copper Emission Factors-

Table 4-76 presents copper emission factors applicable to utility, industrial, and commercial/institutional boilers. Where possible, these were derived from emissions test data. Tables 4-77 through 4-82 summarize measured emission factors reported in the literature. For each combination of combustion sector/coal type/boiler design/control technology, the range and average emission factors are presented. The number of boilers tested and number of test runs are also included on the tables. Information on each copper emissions test, including references, are contained in Appendix C, Tables C-40 through C-49.

Bituminous Coal-Fired Pulverized Dry Bottom Boilers. Seven uncontrolled pulverized dry bottom boilers were tested: 5 utility boilers, 1 industrial boiler, and 1 commercial boiler. Results are summarized in Tables 4-77, 4-80, and 4-82. The industrial boiler had a higher copper emission factor than any of the other boilers, probably due to the fact that the coal it consumed had more than twice the average copper content of bituminous coals. The average emission factor for the other six boilers is 848 $lb/10^{12}$ Btu. Emission factors calculated in other prior studies and presented in Table 4-83 are higher than this measured value; however, the data base for the current study indicates that previous calculations were based on overly conservative (high) estimates of copper content in coal. Bituminous coal

TABLE 4-75. PREVIOUSLY CALCULATED CHROMIUM EMISSION FACTORS FOR COAL COMBUSTION

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor ($lb/10^{12}$ Btu)	Reference
Bituminous	Pulverized Dry Bottom	Uncontrolled	U, I, C	1800-2300	Baig *et al.*, 1981
Bituminous	Pulverized Dry Bottom	Uncontrolled	I, C	6040	Suprenant *et al.*, 1980a; Suprenant *et al.*, 1980b
Bituminous	Pulverized Dry Bottom	Mechanical Ppt.	U, I	1790	Shih *et al.*, 1980b; Suprenant *et al.*, 1980a
Bituminous	Pulverized Dry Bottom	ESP	U, I	128	Shih *et al.*, 1980b; Baig *et al.*, 1981
Bituminous	Pulverized Dry Bottom	Wet Scrubber	U	198	Shih *et al.*, 1980b
Bituminous	Pulverized Wet Bottom	Uncontrolled	U, I	1500-2300	Baig *et al.*, 1981
Bituminous	Pulverized Wet Bottom	Mechanical Ppt.	U	1460	Shih *et al.*, 1980b
Bituminous	Pulverized Wet Bottom	Multiclone	U, I	460	Baig *et al.*, 1981
Bituminous	Pulverized Wet Bottom	ESP	U, I	105	Shih *et al.*, 1980b; Baig *et al.*, 1981
Bituminous	Pulverized Wet Bottom	Wet Scrubber	U	184	Shih *et al.*, 1980b
Bituminous	Cyclone	Uncontrolled	U	320-2300	Baig *et al.*, 1981
Bituminous	Cyclone	Mechanical Ppt.	U	302	Shih *et al.*, 1980b
Bituminous	Cyclone	ESP	U	22	Shih *et al.*, 1980b; Baig *et al.*, 1981
Bituminous	Cyclone	Wet Scrubber	U	32	Shih *et al.*, 1980b

TABLE 4-75. PREVIOUSLY CALCULATED CHROMIUM EMISSION FACTORS FOR COAL COMBUSTION (Continued)

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor ($lb/10^{12}$ Btu)	Reference
Bituminous	Stoker	Uncontrolled	U, I, C	1400-2300	Baig *et al.*, 1981
Bituminous	Stoker	Multiclone	U, I, C	420	Baig *et al.*, 1981
Bituminous	Spreader Stoker	Uncontrolled	I	4650	Suprenant *et al.*, 1980a
Bituminous	Spreader Stoker	Cyclone	I	1370	Suprenant *et al.*, 1980a
Bituminous	Underfeed Stoker	Uncontrolled	C	697	Suprenant *et al.*, 1980b
Bituminous	Automatic Coal-Fired Furnace	Uncontrolled	R	155	DeAngelis and Reznik, 1979
Bituminous	--------	Controlled	C	5.5[b]	Ajax and Cuffe, 1985
Bituminous	--------	Controlled	R	0.49[b]	Ajax and Cuffe, 1985
Lignite	Pulverized Dry Bottom	Uncontrolled	U, I, C	800-2300	Baig *et al.*, 1981
Lignite	Pulverized Dry Bottom	Multiclone	U, I, C	220	Baig *et al.*, 1981
Lignite	Pulverized Dry Bottom	Mechanical Ppt.	U	588	Shih *et al.*, 1980b
Lignite	Pulverized Dry Bottom	ESP	U	21.4	Shih *et al.*, 1980b
Lignite	Pulverized Dry Bottom	Wet Scrubber	U	174	Shih *et al.*, 1980b
Lignite	Cyclone	Uncontrolled	U	700-2300	Baig *et al.*, 1981
Lignite	Cyclone	Mechanical Ppt.	U	569	Shih *et al.*, 1980b

TABLE 4-75. PREVIOUSLY CALCULATED CHROMIUM EMISSION FACTORS FOR COAL COMBUSTION (Continued)

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor ($lb/10^{12}$ Btu)	Reference
Lignite	Cyclone	ESP	U	12	Shih et al., 1980b
Lignite	Cyclone	Wet Scrubber	U	93	Shih et al., 1980b
Lignite	Stoker	Uncontrolled	U, I, C	800-2300	Baig et al., 1981
Lignite	Stoker	Multiclone	U, I, C	220	Baig et al., 1981
Lignite	Automatic Coal-Fired Furnace	Uncontrolled	R	28	DeAngelis and Reznik, 1979
Anthracite	Pulverized Dry Bottom	Uncontrolled	U, I, C	2000-2300	Baig et al., 1981
Anthracite	Stoker	Uncontrolled	U, I, C	120-2300	Baig et al., 1981
Anthracite	Stoker	Uncontrolled	C	465	Suprenant et al., 1980b
Anthracite	Automatic Coal-Fired Furnace	Uncontrolled	R	156	DeAngelis and Reznik, 1979

[a] U = Utility, I = Industrial, C = Commerical/Institutional, R = Residential.

[b] These values are for hexavalent chromium. The boiler type was not given in the reference.

TABLE 4-76. SUMMARIZED COPPER EMISSION FACTORS FOR COAL-FIRED BOILERS

	Emission Factor ($lb/10^{12}$ Btu) by Coal Type		
Boiler Type/Control Status	Bituminous	Lignite	Anthracite
Pulverized Dry Bottom:			
Uncontrolled	848	1490	927
Multiclone	503	884	550
ESP	194	341	212
Scrubber	24	42	26
Pulverized Wet Bottom:			
Uncontrolled	573-848	1010-1490	626-927
Multiclone	340-503	597-884	372-550
ESP	86	151	94
Cyclone:			
Uncontrolled	147-848	258-1490	161-927
Multiclone	87-503	153-884	95-550
ESP	22	39	24
Spreader Stoker:			
Uncontrolled	448-987	787-1730	490-1080
Multiclone	265-590	465-1040	290-645
ESP	67-148	118-260	73-162
Overfeed Stoker:			
Uncontrolled	987-1360	1730-2390	1080-1490
Multiclone	590-806	1040-1420	645-881
ESP	148-204	260-358	162-223

TABLE 4-77. SUMMARY OF MEASURED COPPER EMISSION FACTORS FOR BITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Uncontrolled	735	380-1500	5	19
Mechanical Ppt.	1490	210-3140	2	10
ESP or Mech. Ppt/ESP	205	34-974	7	24
Scrubber	24	10-54	2	3
2 ESPs in Series	34.5	1.6-71	1	5
ESP/Scrubber	14.1	---	1	1
Pulverized Wet Bottom:				
ESP or Mech. Ppt/ESP	85.6	12.3-225	5	5
Scrubber	2.3	---	1	1
Cyclone:				
Uncontrolled	980	610-1350	1	2
ESP	22	0.05-44.2	5	6
Stoker:				
Mechanical Ppt.	265	188-342	2	2
Fabric Filter	5.8	---	1	1

[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-78. SUMMARY OF COPPER EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Range	Number of Boilers	Number of Data Points
Pulverized Coal-Fired:				
ESP	30	---	1	1
Scrubber	29	---	1	1
Cyclone:				
Uncontrolled	1000	---	1	1
Scrubber	170	---	1	1
Unspecified Boiler Type:				
ESP	66	50-82	2	2

TABLE 4-79. SUMMARY OF COPPER EMISSION FACTORS FOR UTILITY BOILERS FIRED WITH LIGNITE COAL

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Multiclone	286	195-376	2	2
ESP	<69.7	---	1	1
Cyclone Boiler:				
Cyclone	480	---	1	1
ESP	30.2	---	1	1
Spreader Stoker:				
Multiclone	193	---	1	1
ESP	46.5	---	1	1

TABLE 4-80. SUMMARY OF MEASURED COPPER EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Uncontrolled	3150	---	1	1
Multiclone	9530	---	1	1
ESP	155	80.6-230	2	2
Multiclone/Scrubber	19.5	---	1	1
Pulverized Wet Bottom:				
Multiclone	45.1	---	1	1
Spreader Stoker:				
Uncontrolled	448	5.2-1100	7	14
Multiclone	790	411-1170	2	2
ESP	171	0.04-309	2	3
Overfeed Stoker:				
Uncontrolled	1930	200-3500	4	5
Economizer/Dust Collector	4550	4200-4900	1	2

[a] Each boiler was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-81. SUMMARY OF MEASURED COPPER EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Number of Boilers	Number of Data Points
Spreader Stoker:				
Uncontrolled	2070	280-3000	2	4
Mechanical Ppt/ESP	46	18-74	1	2

[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-82. SUMMARY OF MEASURED COPPER EMISSION FACTORS FOR COMMERCIAL/INSTITUTIONAL COAL-FIRED BOILERS

Coal Type/ Boiler Type	Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Emission Factor ($lb/10^{12}$ Btu) Range	Number of Boilers	Number of Data Points
Bituminous Coal:					
Pulverized Dry Bottom	Uncontrolled	1410	---	1	1
	Multiclone/ Scrubber	28	---	1	1
Underfeed Stoker	Uncontrolled	5.1	---	1	1
Spreader Stoker	Mechanical Ppt.	184	---	1	1
Overfeed Stoker	Mechanical Ppt.	153	---	1	1
Anthracite Coal:					
Stoker	Uncontrolled	241	232-723	3	3

TABLE 4-83. CALCULATED COPPER EMISSION FACTORS FOR COAL COMBUSTION

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor ($lb/10^{12}$ Btu)	Reference
Bituminous	Pulverized Dry Bottom	Uncontrolled	I, C	2560	Suprenant et al., 1980a; Suprenant et al., 1980b
Bituminous	Pulverized Dry Bottom	Mechanical Ppt.	U, I	740	Shih et al., 1980b; Suprenant et al., 1980a
Bituminous	Pulverized Dry Bottom	ESP	U	54	Shih et al., 1980b
Bituminous	Pulverized Dry Bottom	Wet Scrubber	U	11.2	Shih et al., 1980b
Bituminous	Pulverized Wet Bottom	Mechanical Ppt.	U	604	Shih et al., 1980b
Bituminous	Pulverized Wet Bottom	ESP	U	42	Shih et al., 1980b
Bituminous	Pulverized Wet Bottom	Wet Scrubber	U	10.5	Shih et al., 1980b
Bituminous	Cyclone	Mechanical Ppt.	U	126	Shih et al., 1980b
Bituminous	Cyclone	ESP	U	42	Shih et al., 1980b
Bituminous	Cyclone	Wet Scrubber	U	1.9	Shih et al., 1980b
Bituminous	Spreader Stoker	Uncontrolled	I	1950	Suprenant et al., 1980a
Bituminous	Spreader Stoker	Cyclone	I	558	Suprenant et al., 1980a
Bituminous	Underfeed Stoker	Uncontrolled	C	232	Suprenant et al., 1980b
Bituminous	Automatic Coal-Fired Furnace	Uncontrolled	R	155	DeAngelis and Reznik, 1979
Lignite	Pulverized Dry Bottom	Mechanical Ppt.	U	516	Shih et al., 1980b

TABLE 4-83. CALCULATED COPPER EMISSION FACTORS FOR COAL COMBUSTION (Continued)

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor ($lb/10^{12}$ Btu)	Reference
Lignite	Pulverized Dry Bottom	ESP	U	18.8	Shih et al., 1980b
Lignite	Pulverized Dry Bottom	Wet Scrubber	U	21.1	Shih et al., 1980b
Lignite	Cyclone	Mechanical Ppt.	U	500	Shih et al., 1980b
Lignite	Cyclone	ESP	U	10.0	Shih et al., 1980b
Lignite	Cyclone	Wet Scrubber	U	11.4	Shih et al., 1980b
Lignite	Automatic Coal-Fired Furnace	Uncontrolled	R	70	DeAngelis and Reznik, 1979
Anthracite	Stoker	Uncontrolled	C	93	Suprenant et al., 1980b
Anthracite	Automatic Coal-Fired Furnace	Uncontrolled	R	235	DeAngelis and Reznik, 1979

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

contains an average of 17.8 ppm copper (see Section 3). Assuming all copper in the coal feed is emitted, the maximum emission factor for a boiler burning typical coal would be 1,360 lb/10^{12} Btu. Since not all copper would be emitted, this calculated value is in fair agreement with the average measured emission factor of 848 lb/10^{12} Btu.

A meaningful average emission factor could not be derived from the three data points on pulverized dry bottom boilers controlled with multiclones. Testing of one boiler reported relatively low emissions (210-290 lb/10^{12} Btu) while tests of the other two showed emission factors greater than those for any of the uncontrolled boilers. The coal consumed in one of these boilers had four times the average copper concentration. Since a representative average could not be derived from test data, the summary emission factor shown in Table 4-76 was calculated from the summary uncontrolled emission factor. Based on test data summarized in Table 4-84, it was assumed that multiclones are 40.7 percent efficient for copper removal. The calculated emission factor for pulverized dry bottom boilers controlled with multiclones is 503 lb/10^{12} Btu.

Nine pulverized dry bottom boilers controlled with ESPs have been tested (see Tables 4-77 and 4-80). There is good agreement between measurements at utility and industrial boilers. The average emission factor, weighting each boiler equally, is 194 lb/10^{12} Btu. Four boilers controlled with scrubbers in the utility, industrial, and commercial sectors have been tested. From these tests, the summary average copper emission factor is 24 lb/10^{12} Btu for scrubber-controlled units.

Bituminous Coal-Fired Pulverized Wet Bottom Boilers. Testing of five pulverized wet bottom boilers controlled with ESPs resulted in an average copper emission factor of 86 lb/10^{12} Btu, as shown in Table 4-77. This factor is somewhat lower than that for pulverized dry bottom boilers. This may be due to different levels of copper in the coal feed or to the effects of boiler design. Generally, pulverized wet bottom boilers emit less fly ash than dry bottom boilers.

There are no test data for uncontrolled pulverized wet bottom boilers. Through a review of the literature, it was found that ESPs are about 85 percent efficient for copper removal from combustion source emissions

TABLE 4-84. COPPER REMOVAL EFFICIENCY OF CONTROLS[a]

Control Device	Percent Control Average	Percent Control Range	Number of Boilers	Number of Data Points
Mechanical Ppt.	40.7	35.6-44.7	1	3
ESP	85.0	28.6-99.2	9	29
ESP/Scrubber	97.4	---	1	1
2 ESPs in Series	98.7	97.4-99.94	1	5
Scrubber	91.4	83.0-99.8	2	2

[a] These control efficiencies represent measured control levels reported in the literature. They may or may not be indicative of the long-term performance of these types of controls on copper emissions from combustion sources. The average values should not be construed to represent an EPA-recommended efficiency level for these devices.

(Table 4-84). Using this percentage and an ESP-controlled emission factor of 86 lb/10^{12} Btu, the uncontrolled copper emission factor for wet bottom boilers would be 573 lb/10^{12} Btu. A realistic upper estimate for copper from wet bottom units would be represented by the uncontrolled copper emission factor for pulverized dry bottom boilers (848 lb/10^{12} Btu). This range is presented in Table 4-76.

The summary emission factor for wet bottom boilers controlled with multiclones is derived from the uncontrolled emission factor by assuming 40.7 percent copper control (see Table 4-84). The resulting emission factor range is 340 to 503 lb/10^{12} Btu.

The only tested pulverized wet bottom boiler, controlled by a scrubber, was found to emit 2.3 lb/10^{12} Btu. As shown in Table 4-84, scrubbers in the data base controlled copper with from 83 to 99.8 percent efficiency. Using an average control efficiency of 91.4 percent and the uncontrolled emission range of 573 to 848 lb/10^{12} Btu, the calculated copper emission factor for scrubber control would range from 49 to 71 lb/10^{12} Btu. However, given that some scrubbers may be 99.8 percent efficient, the measured emission factor (2.3 lb/10^{12} Btu) is plausible.

Bituminous Coal-Fired Cyclone Boilers. The summary emission factor for cyclone boilers controlled with ESPs, 22 lb/10^{12} Btu, is based on tests of five boilers. These tests are summarized in Table 4-77. Since cyclone boilers generate less fly ash than pulverized coal-fired boilers, it is reasonable that measured emission factors are lower.

Due to a lack of data, uncontrolled emission factors are calculated from the ESP-controlled factors. A control efficiency of 85 percent is assumed for ESPs, based on test data in Table 4-84. The uncontrolled emission factor calculated using this assumption is 147 lb/10^{12} Btu. Based on the average copper content of bituminous coal (17.8 ppm) and on the assumption that 13.5 percent of total ash from cyclone boilers is emitted as fly ash, the calculated minimum emission factor would be 184 lb/10^{12} Btu. This assumes copper is emitted in the same proportion as total particulates. In reality, copper is often enriched in the fly ash. A realistic upper estimate of uncontrolled copper emissions from cyclone boilers would be the emission factor for pulverized coal-fired boilers (848 lb/10^{12} Btu). Therefore, a range of emission factors (147 to 848 lb/10^{12} Btu) is presented in Table 4-76.

Assuming 40.7 percent of the copper present in an uncontrolled emission stream can be controlled with a multiclone, the emission factor for multiclone-controlled cyclone boilers would range from 87 to 503 lb/10^{12} Btu.

Bituminous Coal-Fired Stoker Boilers. Eleven uncontrolled stoker boilers (seven spreader stokers and four overfeed stokers) were tested. Results are summarized in Table 4-80. The average emission factor for spreader stokers is 448 lb/10^{12} Btu. The average for all eleven stokers, weighting each boiler equally, is 987 lb/10^{12} Btu.

The average measured uncontrolled overfeed stoker emission factor, 1,930 lb/10^{12} Btu, is higher than would be expected given the typical levels of copper in coal. The typical copper content of bituminous coal is 17.8 ppm (Table 3-24). Assuming all of this is emitted, the maximum emission factor would be 1,360 lb/10^{12} Btu. The summary uncontrolled emission factor for overfeed stokers is presented as a range, from 987 lb/10^{12} Btu (the measured average for all stokers) to 1,360 lb/10^{12} Btu (the calculated maximum emission factor for combustion of typical bituminous coal). The measured average emissions level of 1,930 lb/10^{12} Btu is not considered representative.

The average measured emission factor for five utility, industrial, and commercial/institutional spreader stokers controlled with multiclones is 458 lb/10^{12} Btu. This is within the range that would be calculated from the uncontrolled emission factor by assuming 40.7 percent copper control (Table 4-84). The calculated range is 265 to 590 lb/10^{12} Btu. The calculated range for multiclone-controlled overfeed stokers is 590 to 806 lb/10^{12} Btu.

Tests of two spreader stokers controlled with ESPs are summarized in Table 4-80. There was a wide variation in measured emission factors. Testing of nine combustion sources controlled with ESPs showed that ESPs are about 85 percent efficient for copper removal. Applying this efficiency to the uncontrolled emission factors, ESP-controlled spreader stokers would emit from 67 to 148 lb/10^{12} Btu. Overfeed stokers would emit from 148 to 204 lb/10^{12} Btu.

Subbituminous Coal-Fired Boilers. The available emissions test data for subbituminous coal combustion are presented in Tables 4-78 and 4-81. Many studies do not distinguish between bituminous and subbituminous coal. Emission factors specific to subbituminous coal are not presented, but based on the typical copper content of subbituminous and bituminous coals, emission factors for the two types of coal should be similar.

Lignite and Anthracite Coal-Fired Boilers. Emission factors for lignite-fired boilers are summarized in Table 4-79. Testing of three anthracite-fired stoker boilers is summarized in Table 4-82. There are too few data to derive representative emission factors. Emission factors for lignite and anthracite combustion may be derived from the summarized bituminous coal emission factors presented in Table 4-76. The bituminous coal emission factors are multiplied by ratios to account for the differing copper contents and heating values of the three types of coal. Typical copper contents of the coals are shown in Table 3-24, and heating values are summarized in Appendix B. The calculated emission factors are presented in Table 4-76. Calculated lignite and anthracite copper emission factors are higher than bituminous coal emission factors.

Mercury Emission Factors-.

Mercury is the most volatile of the trace elements studied (see Section 3). Essentially 100 percent of the mercury contained in the coal feed is volatilized during combustion and emitted to the atmosphere (Baig et al., 1981). Much of the mercury is emitted in vapor form, although some mercury condenses in the stack and is associated with the fine particulate fractions of the fly ash (Klein et al., 1975b). The literature indicates that the majority of mercury is emitted in the vapor phase, however, the proportion of mercury measured in particulate versus vapor phase varies greatly between tests, and often mass balances do not close well. The form of mercury present in the flue gas is dependent on temperature and on fly ash characteristics. Some literature references also indicate that there have been large margins of error in sample collection and analysis of vapor phase mercury. These factors account for some of the differences in measured mercury emissions between tests.

The distribution of mercury between the vapor and particulate phases determines whether particulate control devices will be effective for mercury control. The available test data indicated in some tests that ESPs resulted in an average of about 50 percent mercury control; however, some tests indicated no, or very little, reduction in mercury emissions. Many of the tests reporting higher mercury control efficiencies for ESPs are suspect due to mass balance closure of less than 50 percent around the boiler and/or control device. It is likely that mercury in the vapor phase escaped detection in some of these tests. There were no test data on the mercury removal efficiency of multiclones, but since multiclones are less efficient than ESPs at small particle collection, very little mercury control would be expected. Two scrubbers tested resulted in 54 and 94 percent mercury control. Scrubbing reduces stack gas temperatures from about 150°C (300°F) to about 52°C (125°F), causing mercury to condense and be removed more effectively (Baig et al., 1981).

Summary mercury emission factors are presented in Table 4-85. These are derived from measured emissions tests and from calculations based on the mercury content of typical coals. Tests of mercury emissions are summarized in Tables 4-86 through 4-91, and previously calculated emission factors are summarized in Table 4-92. Appendix C (Tables C-50 through C-59) contains more information on mercury emissions test results.

Bituminous Coal-Fired Boilers. Bituminous coal contains an average of about 0.21 ppm mercury. Assuming all mercury is volatilized during combustion and emitted, an uncontrolled emission factor of 16 lb/10^{12} Btu would be expected. Since mercury is highly volatile and leaves the boiler in vapor phase, boiler design would have little effect on the expected mercury emissions. As discussed previously, multiclones would not significantly reduce mercury emissions. Thus the 16 lb/10^{12} Btu emission factor would apply to multiclone-controlled as well as uncontrolled boilers. As

TABLE 4-85. SUMMARIZED MERCURY EMISSION FACTORS FOR COAL-FIRED BOILERS

Boiler Type/Control Status	Emission Factor ($lb/10^{12}$ Btu) by Coal Type Bituminous	 Lignite	 Anthracite
All Types of Boilers[a]:			
Uncontrolled	16	21	18
Multiclone	16	21	18
ESP	8-16	10-21	9-18
Scrubber	0.96-7.4	1.2-9.6	1.1-8.3

[a] Boiler types include pulverized coal-fired, cyclone-fired, and stoker boilers.

TABLE 4-86. SUMMARY OF MEASURED MERCURY EMISSION FACTORS FOR BITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Uncontrolled	35	3.9-308	3	12
Mechanical Ppt.	8.5	3.7-21.2	1	7
ESP or Mech. Ppt/ESP	11.0	0.41-22.3	13	42
2 ESPs in Series	0.20	0.011-0.56	1	5
Scrubber	ND[b]	---	1	1
Pulverized Wet Bottom:				
ESP or Mech. Ppt/ESP	4.7	2.6-6.3	5	5
Scrubber	0.16	---	1	1
Cyclone:				
Uncontrolled	10	---	1	1
ESP	8.5	3.95-17.7	5	5
Scrubber	4.9	---	1	1
Stoker:				
Mech. Ppt. or Multiclone	14.2	2.5-26	2	2
Fabric Filter	4.6	---	1	1

[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler and then a mean of these means was calculated.

[b] Not detectable.

TABLE 4-87. SUMMARY OF MEASURED MERCURY EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Range	Number of Boilers	Number of Data Points
Pulverized Coal Fired:				
ESP	4.1	---	1	1
Scrubber	11	---	1	1
Cyclone:				
Uncontrolled	81	---	1	1
Scrubber	4.9	---	1	1
Unspecified Boiler Type:				
ESP	1.8	1.7-2.0	2	2

---

[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-88. SUMMARY OF MEASURED MERCURY EMISSION FACTORS FOR LIGNITE COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Multiclone	5.4	4.4-6.5	2	2
ESP	<0.23	---	1	1
Cyclone Boilers:				
Cyclone	22	---	1	1
ESP	0.46	---	1	1
Spreader Stoker:				
Multiclone	5.6	---	1	1
ESP	0.53	---	1	1

TABLE 4-89. SUMMARY OF MERCURY EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Multiclone	180	---	1	1
ESP	4.25	4.2-4.4	4	4
Multiclone/Scrubber	86	---	1	1
Pulverized Wet Bottom:				
Multiclone	6.7	---	1	1
Spreader Stoker:				
Uncontrolled	3.4	0.76-12	7	14
Multiclone	15.4	5.8-25.1	2	2
ESP	2.95	1.0-4.2	2	3
Overfeed Stoker:				
Uncontrolled	1.3	0.011-2.1	4	5
Economizer/Dust Collector	0.8	0.39-1.2	1	2

[a] Each boiler was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-90. SUMMARY OF MEASURED MERCURY EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Range	Number of Boilers	Number of Data Points
Spreader Stoker:				
Uncontrolled	4.8	0.64-17	2	4
Mechanical Ppt/ESP	0.50	0.37-0.64	1	2

[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-91. SUMMARY OF MEASURED MERCURY EMISSION FACTORS FOR COMMERCIAL/INSTITUTIONAL COAL-FIRED BOILERS

Coal Type/ Boiler Type	Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Range	Number of Boilers	Number of Data Points
Bituminous Coal:					
Pulverized Dry Bottom	Uncontrolled	5.8	---	1	1
	Multiclone/Scubber	1.1	---	1	1
Underfeed Stoker	Uncontrolled	0.42	---	1	1
Spreader Stoker	Mechanical Ppt.	1.4	---	1	1
Overfeed Stoker	Mechanical Ppt.	13.0	---	1	1
Anthracite Coal:					
Stoker	Uncontrolled	5.3	3.5-7.0	3	3

TABLE 4-92. CALCULATED MERCURY EMISSION FACTORS FOR COAL COMBUSTION

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor ($lb/10^{12}$ Btu)	Reference
Bituminous	All Types (Pulverized Dry Bottom, Pulverized Wet Bottom, Cyclone, Stoker, Residential Furnaces)	Uncontrolled	U, I, C, R	16	Baig *et al.*, 1981; Shih *et al.*, 1980b; Suprenant *et al.*, 1980a; Suprenant *et al.*, 1980b; DeAngelis and Reznik, 1979
		Mechanical Ppt.	U, I, C	16	
		ESP	U, I	16	
		Wet Scrubber	U	3.3	
Lignite	Pulverized Dry Bottom or Stoker	Uncontrolled	U, I, C	9.0-26	Baig *et al.*, 1981
Lignite	Pulverized Dry Bottom or Stoker	Multiclone	U, I, C	2.3	Baig *et al.*, 1981
Lignite	Cyclone	Uncontrolled	U	7.6-26	Baig *et al.*, 1981
Lignite	Pulverized Dry Bottom or Cyclone	Multiclone, ESP, or Wet Scrubber	U	23	Shih *et al.*, 1980b
Lignite	Automatic Coal-Fired Furnace	Uncontrolled	R	14	DeAngelis and Reznik, 1979
Anthracite	Pulverized Dry Bottom	Uncontrolled	U, I, C	9-11	Baig *et al.*, 1981
Anthracite	Stoker	Uncontrolled	U, I, C	0.53-11	Baig *et al.*, 1981
Anthracite	Stoker	Uncontrolled	C	4.6	Suprenant *et al.*, 1980b
Anthracite	Automatic Coal-Fired Furnace	Uncontrolled	R	16	DeAngelis and Reznik, 1979

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential

discussed in previous paragraphs, ESPs may result in up to 50 percent mercury control. Therefore, the emission factor for ESP-controlled boilers is expressed as a range, from 8 to 16 lb/10^{12} Btu. Scrubbers were shown to result in 54 to 94 percent mercury control, so emission factors for scrubber-controlled boilers would range from 0.96 to 7.4 lb/10^{12} Btu.

In general, measured bituminous coal emission factors summarized in Tables 4-86, 4-89, and 4-91 support the calculated values. Average emission factors for uncontrolled and multiclone-controlled boilers of various designs range from 1.3 to 35 lb/10^{12} Btu. (One industrial boiler and one utility boiler tested emitted over 180 lb/10^{12} Btu, but these appear to be outliers. The mercury content of the coals for these two tests were not reported, so mass balance calculations are not possible.) The data show no significant differences in mercury emissions between different boiler types or different combustion sectors. The average measured emission factors for various types of ESP-controlled boilers range from 2.9 to 11 lb/10^{12} Btu, and emission factors for scrubber controlled boilers ranged from undetectable amounts to 4.9 lb/10^{12} Btu. (There was one scrubber-controlled boiler emitting 86 lb/10^{12} Btu, but this is an outlier. The mercury content of the coal feed was not reported.) These measured values are in general agreement with the calculated values shown in Table 4-85.

Subbituminous Coal-Fired Boilers. Emission factors for subbituminous coal-fired boilers were not calculated because much of the literature does not distinguish between bituminous and subbituminous coals. Based on mercury content and heating values of the two coals, it would be expected that emission factors for subbituminous coal would be slightly lower than for bituminous coal. The available test data for subbituminous coal combustion are summarized in Tables 4-87 and 4-90.

Lignite and Anthracite Coal-Fired Boilers. Lignite contains about 0.15 ppm and anthracite about 0.23 ppm mercury. Emission factors for lignite and anthracite combustion are presented in Table 4-85. These were calculated using the same procedures that were used to calculate bituminous coal emission factors. The lignite and anthracite emission factors are slightly higher than bituminous coal emission factors. Measured emission factors derived from the available test data on lignite and anthracite fired combustion sources are summarized in Tables 4-88 and 4-91.

Manganese Emission Factors-

Summarized manganese emission factors for coal-fired boilers are presented in Table 4-93. These are based on measurements of manganese emissions and on theoretical calculations. They are applicable to utility, industrial, and commercial/institutional boilers. Tables 4-94 through 4-99 summarize the available manganese emissions data. For the various combustion sector/coal type/boiler design/control technology scenarios, the average and range of measured manganese emission factors are presented. Tables C-60 through C-69, in Appendix C, provide additional information on each emissions test, including references. Previously calculated manganese emission factors are listed in Table 4-100.

Bituminous Coal-Fired Pulverized Dry Bottom Boilers. Six uncontrolled, pulverized dry bottom boilers were tested. Measured emission factors are summarized in Tables 4-94 and 4-99. The average emission factor, weighting each boiler equally is 2,980 lb/10^{12} Btu. This emission factor is similar to previously calculated emission factors listed in Table 4-100.

Data on boilers controlled with multiclones, summarized in Tables 4-94 and 4-97, are highly variable. According to the emissions tests reviewed, multiclones remove about 54.3 percent of the manganese present in the flue gas. Applying this control efficiency to the summary uncontrolled emission factor yields the emission factor of 1,390 lb/10^{12} Btu for bituminous coal-fired pulverized dry bottom boilers controlled with multiclones.

Measured emission factors for 11 pulverized utility boilers and 4 industrial boilers controlled with ESPs are summarized in Tables 4-94 and 4-97. The average emission factor, weighting each boiler equally, is 642 lb/10^{12} Btu. This is the summary emission factor given in Table 4-93.

A total of five pulverized dry bottom boilers controlled with scrubbers were tested. These include utility, industrial, and commercial/institutional boilers. The average emission factor from these tests is 36 lb/10^{12} Btu.

TABLE 4-93. SUMMARIZED MANGANESE EMISSION FACTORS FOR COAL-FIRED BOILERS

	Emission Factor ($lb/10^{12}$ Btu) by Coal Type		
Boiler Type/Control Status	Bituminous	Lignite	Anthracite
Pulverized Dry Bottom:			
Uncontrolled	2,980	16,200	3,070
Multiclone	1,390	7,580	1,430
ESP	642	3,500	661
Scrubber	36	196	37
Pulverized Wet Bottom:			
Uncontrolled	808-2,980	4,410-16,250	832-3,070
Multiclone	377-1,390	2,050-7,580	388-1,430
ESP	177	965	182
Cyclone:			
Uncontrolled	690-1,300	3,760-7,090	710-1,340
Multiclone	322-607	1,760-3,310	332-625
ESP	151	823	155
Scrubber	70-131	382-714	72-135
Stoker:			
Uncontrolled	2,170	11,800	2,230
Multiclone	196-1,010	1,070-5,510	202-1,040
ESP	31-475	169-2,590	32-489

TABLE 4-94. SUMMARY OF MEASURED MANGANESE EMISSION FACTORS FOR BITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Uncontrolled	3040	300-9300	5	20
Mechanical Ppt.	2250	460-4750	2	10
ESP or Mech. Ppt/ESP	635	1.0-9240	11	35
2 ESPs in Series	149	8.05-463	1	5
ESP/Scrubber	28	---	1	1
Scrubber	46	4.6-318	3	6
Pulverized Wet Bottom:				
ESP or Mech. Ppt/ESP	177	7.4-418	5	5
Scrubber	0.95	---	1	1
Cyclone:				
Uncontrolled	1300	1300-1300	1	2
ESP	151	11-314	5	6
Scrubber	126	---	1	1
Stoker:				
Mech. Ppt or Multiclone	246	188-304	2	2
Fabric Filter	18	---	1	1

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[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, then a mean of these means was calculated.

TABLE 4-95. SUMMARY OF MEASURED MANGANESE EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Emission Factor ($lb/10^{12}$ Btu) Range	Number of Boilers	Number of Data Points
Pulverized Coal:				
ESP	43	---	1	1
Scrubber	110	---	1	1
Cyclone:				
Uncontrolled	600	---	1	1
Scrubber	120	---	1	1
Unspecified Boiler Type:				
ESP	27	19-35	2	2

TABLE 4-96. SUMMARY OF MEASURED MANGANESE EMISSION FACTORS FOR LIGNITE COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Emission Factor ($lb/10^{12}$ Btu) Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Multiclone	1620	1560-1680	2	2
ESP	17	---	1	1
Cyclone Boiler:				
Cyclone	1600	---	1	1
ESP	11	---	1	1
ESP/Scrubber	2.94	2.92-2.96	1	2
Spreader Stoker:				
Multiclone	1790	---	1	1
ESP	<10	---	1	1

TABLE 4-97. SUMMARY OF MEASURED MANGANESE EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Multiclone	790	---	1	1
ESP	661	274-790	4	4
Multiclone/Scrubber	15	---	1	1
Pulverized Wet Bottom:				
Multiclone	15	---	1	1
Spreader Stoker:				
Uncontrolled	2310	16-14,000	7	14
Multiclone	103	23.9-183	2	2
ESP	31	10.6-51.4	2	3
Overfeed Stoker:				
Uncontrolled	1930	230-6700	4	5
Economizer/Dust Collector	2050	1100-3000	1	2

[a] Each boiler weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-98. SUMMARY OF MEASURED MANGANESE EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Range	Number of Boilers	Number of Data Points
Spreader Stoker:				
Uncontrolled	10,560	1,300-17,000	2	4
Mech. Ppt/ESP	45	28-62	1	2

[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-99. SUMMARY OF MEASURED MANGANESE EMISSION FACTORS FOR COMMERCIAL/INSTITUTIONAL COAL-FIRED BOILERS

Coal Type/ Boiler Type	Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Range	Number of Boilers	Number of Data Points
Bituminous Coal:					
Pulverized Dry Bottom	Uncontrolled	2680	---	1	1
	Multiclone/Scrubber	26	---	1	1
Underfeed Stoker	Uncontrolled	3.5	--	1	1
Spreader Stoker	Mechanical Ppt.	188	---	1	1
Overfeed Stoker	Mechanical Ppt.	290	---	1	1
Anthracite Coal:					
Stoker	Uncontrolled	114	40-163	3	3

TABLE 4-100. CALCULATED MANGANESE EMISSION FACTORS FOR COAL COMBUSTION

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor ($lb/10^{12}$ Btu)	Reference
Bituminous	Pulverized Dry Bottom	Uncontrolled	U, I, C	2500-3200	Baig et al., 1981
Bituminous	Pulverized Dry Bottom	Uncontrolled	I, C	4180	Suprenant et al., 1980a; Suprenant et al., 1980b
Bituminous	Pulverized Dry Bottom	Mechanical Ppt.	U, I	1260	Shih et al., 1980b; Suprenant et al., 1980a
Bituminous	Pulverized Dry Bottom	ESP	U, I	90	Shih et al., 1980b; Baig et al., 1981
Bituminous	Pulverized Dry Bottom	Wet Scrubber	U	20	Shih et al., 1980b
Bituminous	Pulverized Wet Bottom	Uncontrolled	U, I	2100-3200	Baig et al., 1981
Bituminous	Pulverized Wet Bottom	Mechanical Ppt.	U	1030	Shih et al., 1980b
Bituminous	Pulverized Wet Bottom	Multiclone	U, I	650	Baig et al., 1981
Bituminous	Pulverized Wet Bottom	ESP	U, I	72	Shih et al., 1980b; Baig et al., 1981
Bituminous	Pulverized Wet Bottom	Wet Scrubber	U	19	Shih et al., 1980b
Bituminous	Cyclone	Uncontrolled	U	440-3200	Baig et al., 1981
Bituminous	Cyclone	Mechanical Ppt.	U	214	Shih et al., 1980b
Bituminous	Cyclone	ESP	U	15	Shih et al., 1980b; Baig et al., 1981
Bituminous	Cyclone	Wet Scrubber	U	3.5	Shih et al., 1980b
Bituminous	Stoker	Uncontrolled	U, I, C	1900-3200	Baig et al., 1981
Bituminous	Stoker	Multiclone	U, I, C	580	Baig et al., 1981
Bituminous	Spreader Stoker	Uncontrolled	I	3210	Suprenant et al., 1980a
Bituminous	Spreader Stoker	Cyclone	I	953	Suprenant et al., 1980a

TABLE 4-100. CALCULATED MANGANESE EMISSION FACTORS FOR COAL COMBUSTION (Continued)

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor (lb/10^{12} Btu)	Reference
Bituminous	Underfeed Stoker	Uncontrolled	C	465	Suprenant et al., 1980b
Bituminous	Automatic Coal-Fired Furnace	Uncontrolled	R	4650	DeAngelis and Reznik, 1979
Lignite	Pulverized Dry Bottom	Uncontrolled	U, I, C	4900-14,000	Baig et al., 1981
Lignite	Pulverized Dry Bottom	Multiclone	U, I, C	1300	Baig et al., 1981
Lignite	Pulverized Dry Bottom	Mechanical Ppt.	U	1620	Shih et al., 1980b
Lignite	Pulverized Dry Bottom	ESP	U	58	Shih et al., 1980b
Lignite	Pulverized Dry Bottom	Wet Scrubber	U	70	Shih et al., 1980b
Lignite	Cyclone	Uncontrolled	U	4200-14,000	Baig et al., 1981
Lignite	Cyclone	Mechanical Ppt.	U	1570	Shih et al., 1980b
Lignite	Cyclone	ESP	U	32.5	Shih et al., 1980b
Lignite	Cyclone	Wet Scrubber	U	37	Shih et al., 1980b
Lignite	Stoker	Uncontrolled	U, I, C	4900-14,000	Baig et al., 1981
Lignite	Stoker	Multiclone	U, I, C	1300	Baig et al., 1981
Lignite	Automatic Coal-Fired Furnace	Uncontrolled	R	696	DeAngelis and Reznik, 1979
Anthracite	Pulverized Dry Bottom	Uncontrolled	U, I, C	2000-2300	Baig et al., 1981
Anthracite	Stoker	Uncontrolled	U, I, C	120-2300	Baig et al., 1981
Anthracite	Stoker	Uncontrolled	C	186	Suprenant et al., 1980b
Anthracite	Automatic Coal-Fired Furnace	Uncontrolled	R	156	DeAngelis and Reznik, 1979

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[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

Bituminous Coal-Fired Pulverized Wet Bottom Boilers. The literature contains fewer data on pulverized wet bottom boilers. The average measured emission factor for five utility boilers controlled with ESPs is 177 lb/10^{12} Btu. This is lower than the factor for dry bottom boilers. In general, pulverized wet bottom boilers emit less fly ash than dry bottom boilers.

There are no data on uncontrolled pulverized wet bottom boilers. A review of tests of eight ESP-controlled boilers indicates an average manganese control efficiency of 78.1 percent. By applying this control efficiency to the measured ESP-controlled emission factor of 177 lb/10^{12} Btu, the corresponding uncontrolled emission factor would be 808 lb/10^{12} Btu. A reasonable maximum estimate of uncontrolled manganese emissions from pulverized wet bottom boilers would be the measured uncontrolled emission factor for pulverized dry bottom boilers (2,980 lb/10^{12} Btu). This range of emission factors is summarized in Table 4-93.

Multiclones can result in a 54.3 percent reduction in manganese emissions (Table 4-101). Based on the summarized uncontrolled emission factors of 808 to 2,980 lb/10^{12} Btu, the multiclone-controlled emission factors would range from 377 to 1,390 lb/10^{12} Btu. Assuming scrubbers result in 89.1 percent manganese control (Table 4-101), emission factors for boilers controlled with scrubbers would range from 88 to 324 lb/10^{12} Btu. However, the one measured value (Table 4-94) is well below this range. Data are insufficient to summarize an emission factor for scrubber-controlled pulverized wet bottom boilers.

Bituminous Coal-Fired Cyclone Boilers. Emission factors measured at five cyclone boilers controlled with ESPs are summarized in Table 4-94. The average measured emission factor is 151 lb/10^{12} Btu. Based on this emission factor and a manganese control efficiency of 78.1 percent for ESPs (from Table 4-101), an uncontrolled emission factor of 690 lb/10^{12} Btu can be calculated. One uncontrolled cyclone boiler tested emitted 1,300 lb/10^{12} Btu. The summary uncontrolled emission factor is, therefore, expressed as a range, from 690 to 1,300 lb/10^{12} Btu. The summary multiclone-controlled emission factor of 322 to 607 lb/10^{12} Btu is

TABLE 4-101. MANGANESE REMOVAL EFFICIENCY OF CONTROLS[a]

Control Device	Percent Control Average[b]	 Range	Number of Boilers	Number of Data Points
Mechanical Ppt.	54.3	40.6-63.2	1	3
ESP	78.1	9.4-99.7	8	27
ESP/Scrubber	97.7	---	1	1
2 ESPs in Series	96.4	90.2-99.8	1	5
Scrubber	89.1	80.0-98.2	2	2

[a] These control efficiencies represent measured control levels reported in the literature. They may or may not be indicative of the long-term performance of these types of controls on manganese emissions from combustion sources. The average values should not be construed to represent an EPA-recommended efficiency level for these devices.

[b] Each emission test weighted equally.

calculated based on a control efficiency of 54.3 percent for multiclones (Table 4-101). Assuming 89.1 percent manganese control efficiency, an emission factor of 70 to 131 lb/10^{12} Btu is estimated for cyclone boilers controlled with scrubbers. This is in agreement with the single measured emission factor available.

Bituminous Coal-Fired Stoker Boilers. Since measured manganese emission factors for spreader and overfeed stokers in all three combustion sectors were similar, they were combined to calculate average emission factors applicable to all stokers. The average measured emission factor for eleven uncontrolled stokers (Table 4-97) is 2,170 lb/10^{12} Btu.

The average emission factor for six tests of mechanical precipitator- (or multiclone-) controlled stokers summarized in Tables 4-94, 4-97, and 4-99 is 196 lb/10^{12} Btu. This emissions level is considerably lower than what would be expected based on the uncontrolled emission factor. Assuming 54.3 percent control, the calculated multiclone-controlled emission factor is 1,010 lb/10^{12} Btu. A range of emission factors is presented in Table 4-93 for manganese emissions from multiclone-controlled stokers.

Two stokers controlled with ESPs were found to emit an average of 31 lb/10^{12} Btu. However, the ESP-controlled stoker manganese emissions level that can be calculated, using the determined control efficiency of 78.1 percent and uncontrolled emissions of 2,170 lb/10^{12} Btu, is 475 lb/10^{12} Btu. Because of the degree of variability between the measured and calculated factors, the range of these factors is presented in the emission factor summarization.

Subbituminous Coal-Fired Boilers. Much of the literature does not distinguish between subbituminous and bituminous coals, so summary emission factors for subbituminous coal have not been calculated. The two coals contain similar amounts of manganese (Table 3-36), and emissions would be expected to be similar. The available test data for subbituminous coal-fired utility and industrial boilers are summarized in Tables 4-95 and 4-98.

TABLE 4-102. SUMMARIZED NICKEL EMISSION FACTORS FOR COAL-FIRED BOILERS

Boiler Design/Control Status	Emission Factor ($lb/10^{12}$ Btu) by Coal Type Bituminous	Lignite	Anthracite
Pulverized Dry Bottom:			
Uncontrolled	1030-1290	928-1160	1790-2240
Multiclone	522-654	470-587	906-1140
ESP	280-352	252-316	487-610
Scrubber	37-46	33-42	64-81
Pulverized Wet Bottom:			
Uncontrolled	840-1290	154-1160	1460-2240
Multiclone	425-654	382-587	739-1140
ESP	228-352	205-316	397-610
Scrubber	30-46	27-42	53-81
Cyclone:			
Uncontrolled	174-1290	157-1160	303-2240
Multiclone	88-654	79-587	153-1140
ESP	47-352	43-316	82-610
Scrubber	6.3-46	5.6-42	11-81
Stoker:			
Uncontrolled	775-1290	696-1160	1350-2240
Multiclone	392-654	352-587	683-1140
ESP	211-352	189-316	367-610

TABLE 4-103. VALUES USED IN CALCULATION OF UNCONTROLLED NICKEL EMISSION FACTORS

Coal Type	Concentration of Nickel in Coal, ppm (C)[a]	Heating Value Btu/lb (H)[b]
Bituminous	16.9	13,077
Lignite	8.35	7,194
Anthracite	28.5	12,700

[a] Source: Table 3-42.

[b] Source: Appendix B.

Controlled nickel emission factors are calculated from the uncontrolled emission factors using the average control efficiencies presented in Table 4-104. These control efficiencies are specific to nickel and are derived from tests of controlled coal-fired boilers reported in the literature. The efficiencies shown in Table 4-104 may be biased low due to contamination from sampling equipment corrosion. Emission factors calculated using these efficiencies probably represent, in most cases, upper bound estimates.

Measured nickel emission factors are summarized in Tables 4-105 through 4-110 and in Appendix C, Tables C-70 through C-79. Previously calculated nickel emission factors are listed in Table 4-111. In general, measured uncontrolled and controlled emission factors are higher than the maximum calculated emission factor for the combustion of typical coals. The nickel content of the coal feed (for tests where this was reported) was generally between 10 and 25 ppm, which is similar to the average nickel content of bituminous coal (16.9 ppm). Thus, the high measured average emission factors are not due to the combustion of high-nickel coals. For many tests, mass balances indicate more nickel being emitted than is input in the coal feed. Some references noted that corrosion of sampling train components was suspected to cause the high measured emission factors (Baig et al., 1981). Since it appears that measured nickel emission factors are questionable, the summary values given in Table 4-102 are based on calculations involving fuel content data, element partitioning assumptions, and control efficiency assumptions.

Trace Metal Emission Factors for Residential Coal Combustion-

Summary emission factors for eight trace metals are presented in Tables 4-112 and 4-113. The literature reported only three tests of residential furnaces from which trace metal emission factors could be derived. These were tests of automatic furnaces equipped with stokers, and each was burning bituminous coal. The measured emission factors are summarized in Table 4-114. As can be seen from the table, there is great variability in trace metal emission factors for the three furnaces. This may be due to variations in the trace metal content of the coals and to

TABLE 4-104. NICKEL REMOVAL EFFICIENCY OF CONTROLS[a]

Control Device	Percent Control Average[b]	 Range	Number of Boilers	Number of Data Points
Mechanical Ppt.	49.4	34.5-64.4	1	3
ESP	79.1	48.8-99.5	5	14
2 ESPs in Series	96.6	91.5-99.2	1	5
ESP/Scrubber	97.2	---	1	1
Scrubber	96.4	95.6-97.3	2	2

[a] These control efficiencies represent measured control levels reported in the literature. They may or may not be indicative of the long-term performance of these types of controls on nickel emissions from combustion sources. Although it can not be unequivocally determined with the available data, these control device efficiencies may be biased low due to contamination from sampling equipment. Emission factors calculated using these efficiencies probably represent, in most cases, upper bound estimates. The average values should not be construed to represent an EPA-recommended efficiency level for these devices.

[b] Each emission test weighted equally.

TABLE 4-105. SUMMARY OF MEASURED NICKEL EMISSION FACTORS FOR BITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Uncontrolled	1480	690-5000	4	10
Mechanical Ppt.	7870	260-23,500	2	10
ESP or Mech. Ppt/ESP	2780	520-5760	11	20
2 ESPs in Series	360	132-724	1	4
ESP/Scrubber	12.2	---	1	1
Scrubber	68	12-104	2	5
Pulverized Wet Bottom:				
ESP or Mech. Ppt/ESP	1260	74-2550	5	5
Scrubber	1.1	---	1	1
Cyclone:				
Uncontrolled	960	---	1	1
ESP	907	4.6-2020	5	5
Scrubber	46	---	1	1
Stoker:				
Mech. Ppt. or Multiclone	3260	1330-5180	2	2
Fabric Filter	165	---	1	1

[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-106. SUMMARY OF MEASURED NICKEL EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Range	Number of Boilers	Number of Data Points
Pulverized Coal Fired:				
ESP	70	---	1	1
Scrubber	50	---	1	1
Cyclone:				
Uncontrolled	1700	---	1	1
Scrubber	46	---	1	1
Unspecified Boiler Type:				
ESP	13.2	5.4-21	2	2

TABLE 4-107. SUMMARY OF MEASURED NICKEL EMISSION FACTORS FOR LIGNITE COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Range	Number of Boiler	Number of Data Points
Pulverized Dry Bottom:				
Multiclone	439	267-611	2	2
ESP	<158	---	1	1
Cyclone Boiler:				
Cyclone	740	---	1	1
ESP	<109	---	1	1
Spreader Stoker:				
Multiclone	641	---	1	1
ESP	<88	---	1	1

TABLE 4-108. SUMMARY OF MEASURED NICKEL EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Number of Boilers	Number of Data Points
Pulverized Dry Bottom:				
Multiclone	1,390	---	1	1
ESP	470	10-930	2	2
Multiclone/Scrubber	60	---	1	1
Pulverized Wet Bottom:				
Multiclone	1.5	---	1	1
Spreader Stoker:				
Uncontrolled	5,770	32-20,600	6	12
Multiclone	130	31-230	2	2
ESP	1,020	---	1	1
Overfeed Stoker:				
Uncontrolled	4,610	840-23,000	4	5
Economizer/Dust Collector	22,200	16,500-28,000	1	2

[a] Each boiler was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-109. SUMMARY OF MEASURED NICKEL EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Range	Number of Boilers	Number of Data Points
Spreader Stoker:				
Uncontrolled	2370	840-6500	2	3
Mech. Ppt/ESP	30	---	1	1

[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-110. SUMMARY OF MEASURED NICKEL EMISSION FACTORS FOR COMMERCIAL/INSTITUTIONAL COAL-FIRED BOILERS

Coal Type/ Boiler Type	Control Status	Emission Factor ($lb/10^{12}$ Btu) Average	Emission Factor ($lb/10^{12}$ Btu) Range	Number of Boilers	Number of Data Points
Bituminous Coal:					
Pulverized Dry Bottom	Uncontrolled	2430	---	1	1
	Multiclone/Scrubber	309	---	1	1
Underfeed Stoker	Uncontrolled	30	---	1	1
Spreader Stoker	Mechanical Ppt.	91	---	1	1
Overfeed Stoker	Mechanical Ppt.	1530	---	1	1
Anthracite Coal:					
Stoker	Uncontrolled	825	314-1090	3	3

TABLE 4-111. PREVIOUSLY CALCULATED NICKEL EMISSION FACTORS FOR COAL COMBUSTION

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor ($lb/10^{12}$ Btu)	Reference
Bituminous	Pulverized Dry Bottom	Uncontrolled	U, I, C	1300-1600	Baig et al., 1981
Bituminous	Pulverized Dry Bottom	Uncontrolled	I, C	6740	Suprenant et al., 1980a; Suprenant et al., 1980b
Bituminous	Pulverized Dry Bottom	Mechanical Ppt.	U, I	2020	Shih et al., 1980b; Suprenant et al., 1980a
Bituminous	Pulverized Dry Bottom	ESP	U, I	144	Shih et al, 1980b; Baig et al., 1981
Bituminous	Pulverized Dry Bottom	Wet Scrubber	U	528	Shih et al., 1980b
Bituminous	Pulverized Wet Bottom	Uncontrolled	U, I	1100-1600	Baig et al., 1981
Bituminous	Pulverized Wet Bottom	Mechanical Ppt.	U	1650	Shih et al., 1980b
Bituminous	Pulverized Wet Bottom	Multiclone	U, I	300	Baig et al., 1981
Bituminous	Pulverized Wet Bottom	ESP	U, I	116	Shih et al., 1980b; Baig et al., 1981
Bituminous	Pulverized Wet Bottom	Wet Scrubber	U	495	Shih et al., 1980b
Bituminous	Cyclone	Uncontrolled	U	220-1600	Baig et al., 1981
Bituminous	Cyclone	Mechanical Ppt.	U	342	Shih et al., 1980b
Bituminous	Cyclone	ESP	U	26	Shih et al., 1980b
Bituminous	Cyclone	Wet Scrubber	U	88	Shih et al., 1980b
Bituminous	Stoker	Uncontrolled	U, I, C	970-1600	Baig et al., 1981
Bituminous	Stoker	Multiclone	U, I, C	300	Baig et al., 1981
Bituminous	Spreader Stoker	Uncontrolled	I	5110	Suprenant et al., 1980a
Bituminous	Spreader Stoker	Cyclone	I	1560	Suprenant et al., 1980a

TABLE 4-111. PREVIOUSLY CALCULATED NICKEL EMISSION FACTORS FOR COAL COMBUSTION (Continued)

Coal Type	Boiler Type	Control Status	Sectors[a]	Emission Factor ($lb/10^{12}$ Btu)	Reference
Bituminous	Underfeed Stoker	Uncontrolled	C	930	Suprenant et al., 1980b
Bituminous	Automatic Coal-Fired Furnace	Uncontrolled	R	155	DeAngelis and Reznik, 1979
Lignite	Pulverized Dry Bottom	Uncontrolled	U, I, C	490-1400	Baig et al., 1981
Lignite	Pulverized Dry Bottom	Multiclone	U, I, C	130	Baig et al., 1981
Lignite	Pulverized Dry Bottom	Mechanical Ppt.	U	530	Shih et al., 1980b
Lignite	Pulverized Dry Bottom	ESP	U	19	Shih et al., 1980b
Lignite	Pulverized Dry Bottom	Wet Scrubber	U	374	Shih et al., 1980b
Lignite	Cyclone	Uncontrolled	U	420-1400	Baig et al., 1981
Lignite	Cyclone	Mechanical Ppt.	U	514	Shih et al., 1980b
Lignite	Cyclone	ESP	U	10.5	Shih et al., 1980b
Lignite	Cyclone	Wet Scrubber	U	202	Shih et al., 1980b
Lignite	Stoker	Uncontrolled	U, I, C	490-1400	Baig et al., 1981
Lignite	Stoker	Multiclone	U, I, C	130	Baig et al., 1981
Lignite	Automatic Coal-Fired Furnace	Uncontrolled	R	28	DeAngelis and Reznik, 1979
Anthracite	Pulverized Dry Bottom	Uncontrolled	U, I, C	1000-1200	Baig et al., 1981
Anthracite	Stoker	Uncontrolled	U, I, C	58-1200	Baig et al., 1981
Anthracite	Stoker	Uncontrolled	C	465	Suprenant et al., 1980b
Anthracite	Automatic Coal-Fired Furnace	Uncontrolled	R	156	DeAngelis and Reznik, 1979

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

TABLE 4-112. TRACE METAL EMISSION FACTORS FOR RESIDENTIAL COAL COMBUSTION BY COAL TYPE[a]

	Emission Factor (lb/10^{12} Btu) by Coal Type			
Trace Element	Bituminous	Subbituminous	Anthracite	Lignite
Arsenic	1160	484	453	2380
Beryllium	17.0	13.6	10.4	27.5
Cadmium	52.2	29.8	13.0	57.3
Chromium	157	156	372	188
Copper	136	148	129	239
Mercury	20.7	12.8	12.2	10.0
Manganese	760	1000	790	4200
Nickel	129	73.5	224	116

[a] Calculated emission factors based on average trace element content of each type of coal presented in Section 3.3 (White *et al.*, 1984). It is assumed 100 percent of the mercury input in the coal feed is emitted, 75 percent of the arsenic and cadmium is emitted, and 10 percent of the other trace metals is emitted (DeAngelis and Reznik, 1979). Heating values assumed are 13,077 Btu/lb for bituminous coal, 9,554 Btu/lb for subbituminous, 12,698 Btu/lb for anthracite, and 7,194 Btu/lb for lignite (see Appendix B).

TABLE 4-113. TRACE METAL EMISSION FACTORS FOR RESIDENTIAL COAL COMBUSTION BY REGION OF COAL ORIGIN[a]

Trace Element	Emission Factor ($lb/10^{12}$ Btu) by Region of Coal Origin Appalachian	Interior	Northern Plains	Rocky Mountains
Arsenic	1440	1120	525	392
Beryllium	19.5	20.9	13.6	15.2
Cadmium	8.4	375	24.9	29.0
Chromium	157	248	83.3	218
Copper	157	160	109	153
Mercury	16.0	10.5	18.1	20.8
Manganese	860	910	1100	2200
Nickel	133	244	107	90.6

[a] Calculated emission factors based on average trace element content of coal from these regions presented in Section 3.3 (White et al., 1984). It is assumed that 100 percent of the mercury input in the coal feed is emitted, 75 percent of the arsenic and cadmium is emitted, and 10 percent of the other trace metals is emitted (DeAngelis and Reznik, 1979). Heating values assumed are 11,590 Btu/lb for Appalacian coal; 10,950 Btu/lb for Interior coal; and 9,040 Btu/lb for coal from the Northern Plains and Rocky Mountains.

TABLE 4-114. MEASURED TRACE METAL EMISSION FACTORS FOR BITUMINOUS COAL-FIRED RESIDENTIAL FURNACES

Trace Element	Emission Factor ($lb/10^{12}$ Btu)[a] Average	Range
Arsenic	813	31-2400
Cadmium	71	8.9-155
Chromium	233 (0.49)[b]	44.5-387
Copper	179	38.7-356
Mercury	19.2	7.7-26.7
Manganese	1290	44-3640
Nickel	1110	3.9-3030

[a] Based on testing of three furnaces.

[b] The factor in parentheses is for hexavalent chromium.

variations in combustion and sampling conditions. It was not felt that the average measured emission factor of just three coal samples burned in three furnaces would be representative of residential combustion in general. Therefore, the summarized emission factors in Tables 4-112 and 4-113 are calculated according to the methodology of DeAngelis and Reznik (1979).

The equation is:

$$EF_i = (C_i/H)(F_i) \times 10^6$$

Where: EF_i = emission factor for trace element i (lb/10^{12} Btu),
C_i = concentration of trace element i in coal (ppm),
H = typical heating value of coal (Btu/lb), and
F_i = fraction of trace element input in the coal feed which is emitted to the atmosphere.

Values for C_i are taken from Section 3. Tables in Section 3 report average trace metal contents of different types of coal (bituminous, subbituminous, anthracite, and lignite) as well as averages for each coal-producing region of the country (Appalachian, Interior, Northern Plains, and Rocky Mountains). These average trace metal contents represent hundreds of coal samples.

Heating values (H) by coal type and geographic region are summarized in Appendix B. Footnotes in Tables 4-112 and 4-113 also document the heating values assumed for the calculations.

The fraction of each metal emitted to the atmosphere (F_i) was developed by DeAngelis and Reznik (1979). Values for F_i were based on the observed partitioning behavior of each trace element in two tests of residential furnaces. Where information from these tests was inconsistent, partitioning behavior of the element in larger (utility and industrial) coal-fired boilers was also considered in estimating F_i. DeAngelis and Reznik (1979) recommended F_i values of 1.0 for mercury, 0.75 for arsenic and cadmium, and 0.10 for the other metals. The more volatile the element, the larger the proportion emitted.

The emission factors presented in Tables 4-112 and 4-113 can be used for the residential sector. In general, the average measured emission factors (Table 4-114) are similar to the calculated emission factors. The high measured value for nickel may be due to corrosion of sampling train components.

Lead Emission Factors-

Emission factors for lead from coal combustion are presented in this section. As discussed previously, a limited data base was used to obtain emission factors for lead. They were taken directly from an EPA background document for support of the national ambient air quality standard (NAAQS) (U. S. Environmental Protection Agency, 1985). The emission factors were based on the type of coal burned, bituminous and anthracite. The reference used the premise that utility, industrial, and commercial boilers burned bituminous coal and residential boilers burned anthracite coal. Heating values of 13,077 Btu/lb coal and 12,648 Btu/lb coal were used for bituminous and anthracite coal, respectively to convert the emission factors to a lb lead emitted/10^{12} Btu basis. Uncontrolled and controlled emission factors for lead from coal combustion were calculated to be:

Sector	Uncontrolled Emission Factor (lb/10^{12} Btu)	Controlled Emission Factor (lb/10^{12} Btu)
Utility	507.4	25.37
Industrial	507.4	223.3
Commercial	507.4	223.3
Residential	510.0	510.0

The efficiency of controls were provided in the reference (U. S. Environmental Protection Agency, 1985). For utility boilers, an average control efficiency of 95 percent was applied to coal-fired utility boilers. Control efficiencies for industrial and commercial boilers were reported as 56 percent and no control was assumed for residential boilers.

Additional data concerning measured and calculated emission factors for lead from coal and oil combustion are shown in Tables 4-115 through 4-119.

TABLE 4-115. CALCULATED LEAD EMISSION FACTORS FOR COAL AND OIL COMBUSTION

Coal/Oil Type	Boiler Type	Control Status	Sectors[a]	Emission Factors (lb/10^{12} Btu)	References
Bituminous	Pulverized Dry Bottom	Uncontrolled	U, I, C	3 - 1249	Shih et al., 1980b
Bituminous	Pulverized Dry Bottom	Uncontrolled	I, C	2	Shih et al., 1980b; Krishnan and Hellwig, 1982
Bituminous	Pulverized Dry Bottom	Mechanical Ppt.	U	130	Shih et al., 1980b
Bituminous	Pulverized Dry Bottom	ESP	U, I	70 - 91	Shih et al., 1980b; Krishnan and Hellwig, 1982
Bituminous	Pulverized Dry Bottom	Wet Scrubber	U	2.8 - 24.2	Shih et al., 1980b; Krishnan and Hellwig, 1982
Bituminous	Pulverized Wet Bottom	Uncontrolled	U, I	39 - 60	Shih et al., 1980b; Krishnan and Hellwig, 1982
Bituminous	Pulverized Wet Bottom	Mechanical Ppt.	U	1.1 - 183.8	Shih et al., 1980b; Goldberg and Higgenbotham, 1981
Bituminous	Pulverized Dry Bottom	Multiclones	U, I	12	Shih et al., 1980b; Krishnan and Hellwig, 1982
Bituminous	Pulverized Wet Bottom	ESP	U, I	1.1 - 183.8	Shih et al., 1980b; Krishnan and Hellwig, 1982
Bituminous	Pulverized Wet Bottom	Wet Scrubber	U	6.0	Shih et al., 1980b

TABLE 4-115. CALCULATED LEAD EMISSION FACTORS FOR COAL AND OIL COMBUSTION (Continued)

Coal/Oil Type	Boiler Type	Control Status	Sectors[a]	Emission Factors ($lb/10^{12}$ Btu)	References
Bituminous	Cyclone	Uncontrolled	U	4.0 - 191	Shih et al., 1980b
Bituminous	Cyclone	Mechanical Ppt.	U	9.3	Shih et al., 1980b
Bituminous	Cyclone	ESP	U	4 - 191	Shih et al., 1980b; Krishnan and Hellwig, 1982
Bituminous	Cyclone	Wet Scrubber	U	2559	Shih et al., 1980b
Bituminous	Tangential	Multiclone +2 ESP	U	163	Baig et al., 1981; Goldberg and Higginbotham, 1981
Bituminous	Wall-fired	Multiclone +2 ESP	U	98	Baig et al., 1981; Goldberg and Higginbotham, 1981
Bituminous	Stoker	Uncontrolled	U, I, C	37 - 60	Baig et al., 1981
Bituminous	Stoker	Multiclone	U, I, C	1154 - 1663	Krishnan and Hellwig, 1982
Bituminous	Stoker	Fabric Filter	I	2.6	Shih et al., 1980b
Bituminous	Spreader Stoker	Uncontrolled	I	142	Shih et al., 1980b
Bituminous	Spreader Stoker	Cyclone + ESP + Scrubber	I	50	Shih et al., 1980b
Lignite	Pulverized Dry Bottom	Uncontrolled	U, I, C	15 - 42	Suprenant et al., 1980a

TABLE 4-115. CALCULATED LEAD EMISSION FACTORS FOR COAL AND OIL COMBUSTION (Continued)

Coal/Oil Type	Boiler Type	Control Status	Sectors[a]	Emission Factors ($lb/10^{12}$ Btu)	References
Lignite	Pulverized Dry Bottom	Multiclone	U, I, C	42.1	Suprenant *et al.*, 1980a
Lignite	Pulverized Dry Bottom	ESP	U	5.8	Suprenant *et al.*, 1980a; Shih *et al.*, 1980b; Krishnan and Hellwig, 1982
Lignite	Pulverized Wet Bottom	ESP	U	4.7	Suprenant *et al.*, 1980a
Lignite	Cyclone	Multiclone	U, I	165 - 358	Suprenant *et al.*, 1980a; Shih *et al.*, 1980b; Krishnan and Hellwig, 1982
Lignite	Cyclone	ESP	U	2.6	Suprenant *et al.*, 1980a; Shih *et al.*, 1980b; Krishnan and Hellwig, 1982
Anthracite	Pulverized Dry Bottom	ESP	I	91	Suprenant *et al.*, 1980a; Krishnan and Hellwig, 1982
Anthracite	Stoker	Uncontrolled	U, I, C	0.65 - 13	Krishnan and Hellwig, 1982
Anthracite	Stoker	Multiclone		1419	Krishnan and Hellwig, 1982
Anthracite	Stoker	Uncontrolled	C	2.3	Krishnan and Hellwig, 1982

TABLE 4-115. CALCULATED LEAD EMISSION FACTORS FOR COAL AND OIL COMBUSTION (Continued)

Coal/Oil Type	Boiler Type	Control Status	Sectors[a]	Emission Factors ($lb/10^{12}$ Btu)	References
Residual	Tangential	ESP	U, I	9.3	Goldberg and Higginbotham, 1981; Krishnan and Hellwig, 1982
Residual	Tangential	Uncontrolled	U, I	46.5	Goldberg and Higginbotham, 1981; Krishnan and Hellwig, 1982
Residual	Wall	ESP	U, I	9.3	Goldberg and Higginbotham, 1981; Krishnan and Hellwig, 1982
Residual	Wall	Uncontrolled	U, I	46.5	Krishnan and Hellwig, 1982
Distillate	Tangential	Uncontrolled	I	46.5	Krishnan and Hellwig, 1982
Distillate	Wall	Uncontrolled	I	46.5	Krishnan and Hellwig, 1982

[a] U = Utility, I = Industrial, C = Commercial/Institutional

TABLE 4-116. SUMMARY OF MEASURED LEAD EMISSION FACTORS FOR BITUMINOUS COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Range	Number of Boilers Tested	Number of Data Points
Pulverized Dry Bottom:				
Uncontrolled	316	2.8 - 1249	4	5
ESP or Mechanical Ppt./ESP	49	7.0 - 90.9	2	26
Scrubber	16.8	2.8 - 24.2	3	2
Tangential Cyclone + 2 ESP	163	95 - 282	1	4
Wall Fired Cyclone + 2 ESP	98	76 - 107	1	4
Pulverized Wet Bottom:				
ESP	63.8	1.1 - 183.8	7	7
Mechanical Ppt./ESP	646	---	1	1
Scrubber	22.3	22.3	1	1
Cyclone:				
ESP	15.3	4.0 - 19.2	6	6
Mechanical Ppt.	213	---	1	1
Wet Scrubber	4	---	1	1
Stoker:				
Mechanical Ppt. or Multiclone	1408	1154 - 1663	3	3
Fabric Filter	2.6	---	1	1
Cyclone + ESP + Scrubber	50	0.2 - 149	2	4

---

[a] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

TABLE 4-117. SUMMARY OF LEAD EMISSION FACTORS FOR UTILITY BOILERS

Coal/ Oil Type	Boiler Type/ Control Status	Emission Factor (lb/10^{12} Btu)		Number of Boilers Tested
		Average	Range	
Anthracite	**Pulverized Dry Bottom:**			
	ESP	91	---	1
	Stoker:			
	Multiclones	1419	---	1
Lignite	**Pulverized Dry Bottom:**			
	ESP	9.7	5.8 - 13.5	3
	Multicyclones	154	42.1 - 256	3
	Pulverized Wet Bottom:			
	ESP	4.7	---	1
	Cyclone:			
	ESP	18	9.0 - 26.1	1
	Multicyclones	358	---	1
	Stoker:			
	ESP	6	---	1
	Multicyclones	217	153.5 - 281	1
Residual Oil	**Tangential:**			
	ESP	9.3	---	---
	Uncontrolled	47	16.0 - 112.0	2
	Wall:			
	ESP	9.3	---	---
	Uncontrolled	47	16.0 - 112.0	2

TABLE 4-118. SUMMARY OF LEAD EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Boiler Type/ Control Status	Emission Factor ($lb/10^{12}$ Btu)		Number of Boilers Tested	Number of Data Points
	Average	Range		
Pulverized Dry Bottom:				
Uncontrolled	2	---	1	1
Multiclone	0.65	---	1	1
ESP	91	---	6	6
Multiclone/Scrubber	24	---	1	1
Spreader Stoker:				
Uncontrolled	1.6	---	---	---
Multiclone	0.49	---	---	---
ESP	1.2	---	---	---

TABLE 4-119. SUMMARY OF MEASURED LEAD EMISSION FACTORS FOR COMMERCIAL/INSTITUTIONAL BOILERS

Coal Type/ Boiler Type	Control Status	Emission Factor ($lb/10^{12}$ Btu)		Number of Boilers	Number of Data Points
		Average	Range		
Bituminous Coal:					
Pulverized Dry Bottom	Multiclone	374	---	1	1
Stoker	Scrubber	20	---	1	1
	Multiclone	281	---	2	2
	Uncontrolled	656	---	2	2
Residual Oil:					
Tangential	Uncontrolled	52	16.0 - 186.0	4	4
	Scrubber	7.1	4.7 - 9.5	2	2
Wall	Uncontrolled	52	16.0 - 186.0	2	2
	Scrubber	7.1	4.7 - 9.5	2	2
Distillate Oil:					
Tangential	Uncontrolled	85	47 - 112.0	3	3
Wall	Uncontrolled	85	47 - 112.0	3	3

Source: Suprenant *et al.*, 1980b; Goldberg and Higginbotham, 1981.

Radionuclide Emission Factors

Measured U-238 emission factors for twenty-one utility boilers were reported in the literature. These data are summarized in Table 4-120. Information on each test, including the type of coal burned and the literature reference, is included in Appendix C (Table C-80). Thorium emission factors for fourteen boilers were reported in the literature. These data are summarized in Table 4-121 and in Appendix C (Table C-81).

Pulverized dry bottom boilers controlled with ESPs are the most common type of utility boiler and are also the best characterized in terms of uranium and thorium emissions. The average U-238 emission factor for eight boilers of this type is 6.55 picoCuries per gram of particulate emissions (pCi/g), and the average thorium emission factor is 3.0 pCi/g. For those tests where coal heating values and input rates were reported, radionuclide emissions can also be expressed in terms of pCi/10^6Btu heat input. The average emission factors for U-238 and Th-232 are 295 and 170 pCi/10^6 Btu, respectively. Uranium-238 emissions expressed in this manner vary over 2 orders of magnitude for the eight sources tested. This is a function of the wide variation in total particulate (including uranium) emissions between boilers. The ratio of uranium to total particulate emissions (pCi/g) is much less variable between tests.

Measured U-238 and Th-232 emission factors for pulverized dry bottom boilers controlled with scrubbers are also summarized in Tables 4-120 and 4-121. From the limited data available, it appears that radionuclide emission factors for boilers controlled with scrubbers are similar to emission factors for boilers controlled with ESPs.

Data on cyclone and stoker boilers controlled with ESPs, scrubbers, and fabric filters are also included in Tables 4-120 and 4-121. The data base is too limited to draw conclusions about representative U-238 and Th-232 emission factors for cyclone and stoker boilers. In general emission factors are on the same order of magnitude as emission factors for pulverized dry bottom boilers.

Very few data were available concerning uncontrolled emission factors for radionuclides from coal-fired boilers. An estimate of 30,000 pCi/10^6 Btu (for U-238 only) was developed for utility boilers by back calculating

TABLE 4-120. SUMMARY OF MEASURED URANIUM-238 EMISSION FACTORS FOR COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor (pCi/g)[a]		Emission Factor (pCi/10^6 Btu)[b]		Number of Boilers Tested
	Average[c]	Range	Average[c]	Range	
Pulverized Dry Bottom:					
ESP	6.55	3.3-9.2	295.3	6.3-675.9	8
ESP/Scrubber	7.1	---	22.5	---	1
Scrubber	5.6	---	73.7	---	1
Pulverized Slag Bottom:					
Mechanical Ppt/ESP	0.004	---	---	---	1
Cyclone:					
ESP	1.5	0.005-3.0	68.0[d]	---	2
Scrubber	13.9	0.017-37.5	1757.8[e]	301.2-3214.3[e]	3
Stoker:					
Fabric Filter	0.003	---	---	---	1
ESP	0.5	---	13.8	---	1
Unspecified:					
ESP	16.1	7-34.2	294[e]	101.6-486.5[e]	3

[a] PicoCuries per gram of particulate emissions.

[b] PicoCuries emitted per 10^6 Btu input.

[c] Each boiler tested was weighted equally in determining this average. An arithmetic mean was calculated for each boiler, and then a mean of these means was calculated.

[d] Average value from one unit. No heating value was available for the other unit, so emission factor could not be expressed in terms of pCi/10^6 Btu.

[e] Average value from two units. No heating value was available for the other unit, so emission factor could not be expressed in terms of pCi/10^6 Btu.

TABLE 4-121. SUMMARY OF MEASURED THORIUM-232 EMISSION FACTORS FOR COAL-FIRED UTILITY BOILERS

Boiler Type/ Control Status	Emission Factor (pCi/g)[a]		Emission Factor (pCi/10^6 Btu)[b]		Number of Boilers Tested
	Average[c]	Range	Average[c]	Range	
Pulverized Dry Bottom:					
ESP	3.0	0.6-5.3	170.0	50.3-180.7	8[d]
ESP/Scrubber	7.14	---	22.7	---	1
Scrubber	2.78	---	36.5	---	1
Cyclone:					
ESP	1.8	---	40.8	---	1
Scrubber	2.09	1.5-2.68	170.0	110.2-229.7	2
Stoker:					
ESP	0.5	---	13.8	---	1

[a] PicoCuries per gram of particulate emissions.

[b] PicoCuries emitted per 10^6 Btu heat input.

[c] Each boiler tested was weighted equally in determining this average. An arithmetic mean value was calculated for each boiler, and then a mean of these means was calculated.

[d] Data from 7 of 8 boilers tested were used for calculations. The reference for the excluded test noted that the error may be ≥30 percent.

from the controlled emission factors for five utility boilers. The boiler types included one stoker, one cyclone, two pulverized coal-dry bottom and one pulverized coal tangentially-fired boiler. One boiler burned subbituminous coal and the remaining boilers burned lignite coal. The high and low ends of the range of amount of radioactivity in the coal were averaged in back calculating the uncontrolled emission factor.

There is a potential that the type of coal burned may affect U-238 and Th-232 emission factors. Tables 3-48 and 3-52 indicate that lignite coal has higher average total uranium and thorium concentrations than bituminous coal. However, the standard deviations around the mean values are larger than the means themselves, indicating great variability in the data. Emissions test data for four lignite boilers and several bituminous coal boilers are shown in Tables C-80 and C-81. These data do not show a strong correlation between type of coal burned and measured radionuclide emission factors.

POM Emission Factors

The measurement of POM emissions from combustion sources has been a focus of recent research. Factors affecting the formation and emission of POM are discussed in Section 3. Based on theoretical considerations, it is predicted that pulverized coal-fired boilers would emit less POM than cyclone boilers, which in turn would emit less POM than stoker boilers. It was also postulated that larger boilers would emit less POM per unit of heat input than smaller boilers. Measured emission factors reported in the literature support these conclusions.

The same considerations given previously for evaluating POM emissions data from oil combustion apply equally to the evaluation of POM emissions from coal combustion. In assessing total POM emission factors for coal combustion, the following factors should be analyzed.

- the methods used to take and analyze samples
- the measurement of particulate POM only or of gaseous and particulate POM

- the physical phase in which emissions predominantly occur
- the number of POM compounds analyzed for
- the specific POM compounds analyzed for

The individual source POM emissions data given in Appendix C, Tables C-82 through C-87, are characterized according to the evaluation criteria listed above. However, as with the oil combustion results, the summary total POM data for coal combustion in Table 4-122 does not distinguish total POM according to the number of compounds analyzed for, the test methods used, etc. The reader can consult Tables C-82 to C-87 to determine the level of inconsistency among the summarized reported total POM emission results.

Measured POM emission factors for about 90 coal-fired boilers and furnaces are summarized in Tables C-82 through C-87 in Appendix C. Based on the available data, it does not appear that coal type or particulate control - technology have a significant effect on measured emission factors. Therefore, data have been summarized by sector and by boiler type regardless of control technology. Table 4-122 presents the average measured emission factor and range of emission factors for each sector and type of boiler.

Table 4-122 shows that pulverized coal-fired utility boilers have the lowest POM emission factors, averaging 3.9 $lb/10^{12}$ Btu. Cyclone boilers have higher emission factors; and utility stoker boilers emit more POM per unit of heat input than other types of utility boilers.

Measured POM emission factors for industrial pulverized coal-fired boilers are also relatively low, averaging 35.3 $lb/10^{12}$ Btu. A large number of industrial, commercial, and residential stoker boilers have been tested. As shown in Table 4-122, measured POM emissions for stoker boilers are highly variable. Reported emission factors vary over three orders of magnitude. Average POM emission factors for stokers in the industrial, commercial, and residential sectors are quite high (~100 to 3000 $lb/10^{12}$ Btu). The reasons for the extreme variability in the data are unknown. Sources of variation would include sampling and analytical methodology, type of coal, boiler design (spreader versus underfeed), boiler size, and operating parameters. Most commercial and residential boilers tested were underfeed stokers, and were probably smaller than the industrial

TABLE 4-122. SUMMARY OF MEASURED TOTAL POM EMISSION FACTORS FOR COAL-FIRED SOURCES

Sector/Boiler Type	Emission Factor ($lb/10^{12}$ Btu) Average[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Number of Boilers Tested
Utility:			
Pulverized Coal[b]	3.9[c]	0.03-18.6	24
Cyclone[d]	9.0	0.11-57.2	10
Stoker[e]	29.6	0.13-114	8
Industrial:			
Pulverized Coal[f]	35.3	2.8-121	6
Stoker[g]	96.0	2.7-413	17
Residential/Commercial:[h]			
Stoker	3,046	13.8-18,000	25
Hand Stoked	26,095	57.5-84,600	5
Magazine Feed	2,717	9.7-8,177[i]	4

[a] Each boiler tested was weighted equally in calculating these averages.

[b] Six boilers were controlled with ESPs, four with combination multicyclone/ESP systems, three with cyclones, two with wet scrubbers, one was uncontrolled, and the control status of ten was not reported.

[c] One boiler with a POM emission factor of 565 $lb/10^{12}$ Btu was excluded from these calculations because it was an outlier to the data set. If this boiler was included, the average would be 23.9 $lb/10^{12}$ Btu.

[d] Eight boilers were controlled with ESPs and one with a wet scrubber; the control status of the other boiler was not reported.

[e] Four boilers were controlled with cyclones, one with a fabric filter, and control status of the other three was not reported.

[f] Three boilers were controlled with multicyclone/ESP systems, two with ESPs, and one with a multicyclone.

[g] One boiler was controlled with an ESP, one with a multicyclone, and the remaining 15 were uncontrolled.

[h] Category includes residential and small commercial boilers. All were uncontrolled.

[i] The range for bituminous coal is 2,632 to 8,177 $lb/10^{12}$ Btu, with the average being 5,404 $lb/10^{12}$ Btu. The range for anthracite coal is 9.7 to 49.4 $lb/10^{12}$ Btu, with the average being 29.6 $lb/10^{12}$ Btu.

stokers tested. These factors may partially explain the higher average POM emission factor for small commercial/residential stokers compared to industrial stokers.

Data on three hand stoked residential units are highly variable, but indicate that hand stoked combustion sources may have significantly higher POM emissions than automatic stokers.

Formaldehyde Emission Factors

There are insufficient data on formaldehyde to characterize emissions by boiler type or combustion sector. Only one reference was identified which contained measured formaldehyde emission factors. The seven individual tests are summarized in Table 4-123. Emission factors range from 63 to 2,100 $lb/10^{12}$ Btu, with an average of 446 $lb/10^{12}$ Btu. The average would be 170.5 $lb/10^{12}$ Btu if the apparent outlier of 2100 $lb/10^{12}$ Btu is excluded from the calculation. The fact that a hand stoked unit had the lowest emission factor is inconsistent with theory. The two tests of pulverized coal-fired boilers indicate that these units may have slightly lower emission factors than stoker boilers; however, the number of tests is too few to make this conclusion with certainty.

Since formaldehyde is a product of incomplete combustion, it is likely that modern units, particularly for utilities, would have lower emissions than those in these tests which date to the mid-1960's. Additional emissions testing is clearly needed to establish reliable boiler emission factors for formaldehyde.

TABLE 4-123. MEASURED FORMALDEHYDE EMISSION FACTORS FOR COAL-FIRED BOILERS AND FURNACES

Emission Factor ($lb/10^{12}$ Btu)	Boiler Type	Sectors[a]	Control Status	Reference
130	Pulverized Dry Bottom	U	Uncontrolled	Hangebrauck *et al.*, 1964
90	Pulverized Dry Bottom	I	Uncontrolled	Hangebrauck *et al.*, 1964
140	Chaingrate Stoker	U	Uncontrolled	Hangebrauck *et al.*, 1964
220	Spreader Stoker	I	Uncontrolled	Hangebrauck *et al.*, 1964
2100	Underfeed Stoker	I	Uncontrolled	Hangebrauck *et al.*, 1964
380	Underfeed Stoker	C	Uncontrolled	Hangebrauck *et al.*, 1964
63	Hand Stoked	R	Uncontrolled	Hangebrauck *et al.*, 1964

[a] U = Utility, I = Industrial, C = Commercial/Institutional, R = Residential.

SECTION 5
SOURCE TEST PROCEDURES

This section contains a collection of sampling and analysis procedures that have been used to quantify trace metal, POM, formaldehyde, and radionuclide emissions from coal and oil combustion sources. With the exception of real time techniques, quantification of emissions involves three steps: (1) sample collection, (2) sample recovery and preparation, and (3) quantitative analysis. This section briefly describes general methodologies associated with each of these steps that have been published in the literature. No attempt has been made to produce an exhaustive listing or a detailed description of the many methodologies that have been used. The purpose of this section is to present basic sampling and analysis principles and examples of how these principles have been applied to various combustion sources. The presentation of these published methods in this report does not constitute endorsement or recommendation or signify that the contents necessarily reflect the views and policies of the U. S. Environmental Protection Agency. Separate discussions are provided for trace metals, POM, formaldehyde, and radionuclides.

TRACE METALS

Recent research has been sponsored by EPA that was focused on developing source test procedures for trace metals from combustion sources (Osmond et al., 1988). The recommended sampling and analysis procedures produced by this research are described here. The recommended procedures are designed to quantify the following trace metals: lead, zinc, chromium, copper, nickel, manganese, selenium, arsenic, beryllium, thallium, silver, antimony, phosphorus, and barium. In cases where only arsenic, lead, mercury, or beryllium specifically are of interest, the reader may want to use specific EPA reference methods that have been published in 40 CFR Part 61 for these metals. The reference methods are identified below:

Lead - Reference Method 12
Mercury - Reference Methods 101, 101A
Beryllium - Reference Methods 103, 104
Arsenic - Reference Method 108

For mercury, Reference Methods 101 and 101A are similar and differ primarily in the solution used for sample collection (acidic iodine monochloride in 101 and acidic potassium permanganate in 101A). Method 101 was promulgated for use at chlor-alkali plants, while Method 101A was developed sewage sludge incinerators. For applications to combustion sources, 101A would likely be more appropriate. Reference Method 103 for beryllium is a screening method to indicate the relative presence of beryllium. Method 104 is a more quantitative set of procedures that can be used to effectively measure beryllium releases from combustion sources.

The recommendation from the recent combustion source trace metals test method research are summarized below.

Sampling Method

The sampling system design that was found to be the most desirable for trace metals from combustion sources is a modified EPA Method 5 train due to its particulate collection efficiency, ease of operation, availability, and cost (Osmond et al., 1988). The absorbing solutions identified to collect the trace metals include nitric acid, hydrogen peroxide, and acidified potassium permanganate. The configuration and components of the sampling train contained an EPA Method 5 glass probe, a heated filter box containing a quartz fiber filter, an empty condensate collecting impinger, two 5 percent nitric acid/10 percent hydrogen peroxide impingers, one impinger containing acidified permanganate, a silica gel impinger, and the usual EPA Method 5 meter box and vacuum pump. The Method 5 train is illustrated in Figure 5-1. The recommended impinger design in shown in Figure 5-2.

This design was evaluated in the laboratory by spiking the absorbing solutions with the metals of interest and digesting three samples either with conventional heating or open vessel microwave digestion methods. Both

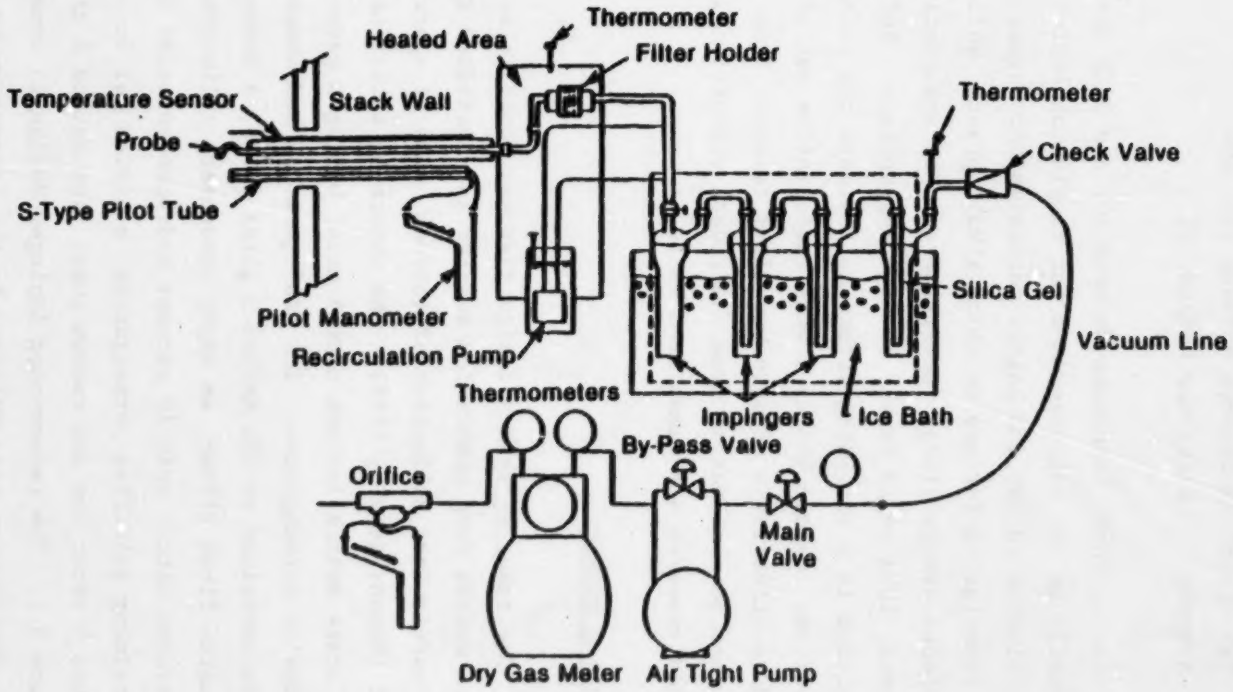
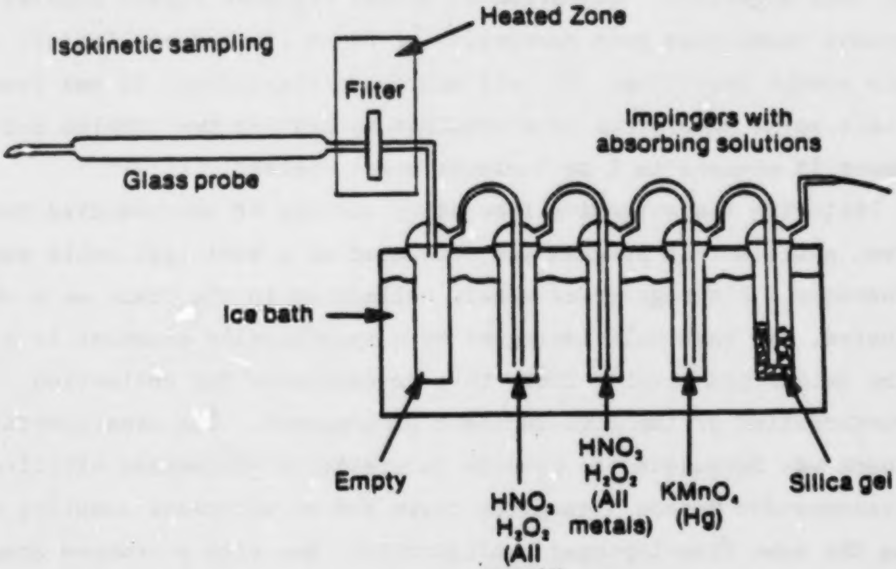

Thermometer
Heated Area
Filter Holder
Temperature Sensor
Stack Wall
Thermometer
Probe
Check Valve
S-Type Pitot Tube
Silica Gel
Pitot Manometer
Vacuum Line
Recirculation Pump
Thermometers
Impingers
Ice Bath
By-Pass Valve
Orifice
Main
Valve
Dry Gas Meter
Air Tight Pump

Figure 5-1. Modified EPA Method 5 Train



Heated Zone
Isokinetic sampling
Filter
Impingers with absorbing solutions
Glass probe
Ice bath
Empty
HNO_3 H_2O_2 (All metals)
HNO_3 H_2O_2 (All metals)
$KMnO_4$ (Hg)
Silica gel

Figure 5-2. Recommended Impinger Design

digestion methods were found to yield recoveries of 100 ± 20 percent of the spiked metals. However, discounting the time involved in initially evaporating the sample to near dryness, the microwave method was approximately eight times faster than the conventional heating method.

High purity filters were also spiked with the metals of interest and digested using either Parr® Bombs or microwave pressure relief vessels. Analysis of the samples showed that both digestion methods gave recoveries of 100 ± 20 percent for the spiked metals, but the microwave pressure relief vessel digestion was approximately 20 times faster than the conventional Parr® Bomb digestion. Digestion of spiked baghouse flyash samples using microwave techniques gave recoveries of 70 to 100 percent for all of the metals except beryllium. For all microwave digestions, it was found that the best spike recoveries were obtained by heating the samples for a total of about 15 minutes in 1 to 3-minute power cycles.

Following the extensive laboratory testing of the modified Method 5 system, a field test program was conducted at a municipal solid waste incinerator. Although trace metals collection in the train as a whole was evaluated, the back-half impingers were specifically examined to see first if the metals had reached them, then to determine the collection characteristics of the five impinger arrangement. The experimental test approach was formulated to compare the relative collection efficiencies of the recommended Method 5 sampling train and an alternate sampling train using the same five impinger configuration, but with a reduced absorbent strength (i.e., 0.1 N HNO_3 instead of 5 percent HNO_3) in two of the impingers. Furthermore, samples were collected to compare the mercury collection efficiency of the proposed Method 5 sampling train to that of EPA Method 101A for mercury.

The results of the analytical data analyses indicate that there are no significant differences between the metals collection ability of 0.1 N nitric acid and 5 percent nitric acid. The recommended Method 5 sampling train was also found to be similar statistically to the EPA Method 101A in collecting mercury. Front- and back-half metal distributions indicate that, with the exception of mercury, arsenic, barium, and phosphorus, most of the metals are captured in the front-half or filter section of the train.

Analytical Method

There are a number of methods described in the literature for measuring low levels of trace metals. These analytical methods include atomic absorption spectroscopy (AAS), inductively coupled plasma argon spectroscopy (ICAP), differential pulse anodic stripping voltametry (ASV), optical emission spectroscopy [OES (DC arc/AC spark)], X-ray fluorescence (XRF), neutron activation analysis (NAA), particle induced X-ray emission analysis (PIXIE), and spark source mass spectrometry (SSMS). A comparison of the detection limits of these techniques is given in Table 5-1.

The analytical technique recommended for use with the modified Method 5 sampling procedure is ICAP (Osmond et al., 1988). ICAP is an attractive method for the analysis of most elements due to its low cost, acceptable sensitivity, and multi-element analysis capabilities. ICAP can be combined with AAS for those elements, such as mercury, arsenic, selenium, and lead, for which ICAP is not as sensitive.

General instrument availability is a factor in choosing a recommended analytical method. ICAP and AAS are generally more available than the nondestructive methods for XRF or NAA. Samples should first be analyzed by ICAP for all elements except mercury. An analysis for mercury can be done using cold vapor atomic absorption. If lead, arsenic, and selenium are not found in the ICAP analysis or are found at levels at or near the detection limits, the samples should be reanalyzed for these elements using AAS. Lead should be analyzed by flame AAS, but selenium and arsenic should either be analyzed using a graphite furnace or hydride method. Based upon the minimum detection limits for ICAP and AAS and assuming a sampling time of 2 hours and a sampling rate of 10 L/minute, this method combination could be used to detect the elements in question at ppb levels in stack gas, as shown in Table 5-2. NAA can be used to supplement the ICAP/AAS method if NAA is available and proper standards can be obtained.

TABLE 5-1. COMPARISON OF DETECTION LIMITS FOR DIFFERENT ANALYTICAL METHODS

Analytical Methods	Elements											
	Cd	Cr	Ni	Mn	As	Be	Cu	Hg	Zn	Pb	Se	P
Inductively Coupled Plasma Spectroscopy (ICAP) **in ppb	1	2	5	0.5	20	3	2	25	1	20	30	75
Atomic Absorption Spectroscopy (AAS) **in ppb	1	2	8	3	0.2	20	2	0.001	0.6	10	0.1	290
Optical Emission Spectroscopy (OES) **in ppb	10,000	5,000	5,000	1,000	50,000	500	500	50,000	10,000	5,000	500,000	50,000
Differential Pulse Anodic Stripping **in ppb	5	NA	NA	NA	0.6	NA	5	NA	5	5	8	NA
Neutron Activation Analysis (NAA) **in ng[a]	0.4	50	20	0.004	0.2	NA	0.1	10	8	NA	2	NA
Spark Source Mass Spectroscopy **in ng	0.3	0.05	0.07	0.05	0.06	0.008	0.08	0.6	0.1	0.3	0.1	0.03
X-ray Fluorescence (XRF) **in ng/cm^2 [b]	NI	4.4	4	3.9	72	NI	10.9	NI	5	276	NI	NI
Particle Induced X-ray Emission Analysis (PIXIE)	c	c	c	c	c	NA	c	c	c	c	c	c

[a] The elements from Na through Hg can be detected at ppb sensitivities with NAA.

[b] Generally, XRF can measure from ppm to percentage compositions.

[c] For PIXIE, sensitivities range from 1,000 to 10,000 ug/cm^2 for elements with atomic numbers from approximately 16 to 82.

NA = not applicable.
NI = information not available.

TABLE 5-2. MINIMUM DETECTABLE LEVELS OF METALS IN THE STACK GAS

Elements	Analytical Detection Limit (Ideal) (ppb)[a]	Analytical Detection (Typical) (ppb)[a]	Concentration in the Stack Gas (Ideal) (ppb)[b]	Concentration in the Stack Gas (Typical) (ppb)[b]
Cd	1	20	0.0182	0.3638
Cr	2	50	0.0783	1.9583
Ni	5	35	0.1725	1.2075
Mn	0.5	2	0.0185	0.0742
As	0.2	1	0.0054	0.0272
Be	3	5	0.6793	1.1321
Cu	2	30	0.0637	0.9550
Hg	0.001	0.5	0.0000	0.0051
Zn	1	5	0.0313	0.1567
Pb	10	100	0.0984	0.9842
Se	0.1	3	0.0026	0.0773
P	76	250	4.9970	16.4375

Note: Final Sample Size = 100 mL
Sampling Rate = 10 L/min
Sampling Time = 120 min

[a] Concentration in ng/mL (in solution).

[b] Volume/volume concentration in the stack gas.

POLYCYCLIC ORGANIC MATTER

The major objective of POM measurement is the quantitative capture and recovery of both particle-bound and vapor phase constituents, while simultaneously preserving the integrity of the sample. A second important factor in sample collection is the ability to capture sufficient quantities to allow subsequent chemical analysis. Although collection methods take different forms, most are similar in principle, utilizing both filtration and adsorption collection techniques. The sampling and analytical methods for this document were extracted from a recent EPA report on POM entitled "Locating and Estimating Air Emissions from Sources of Polycyclic Organic Matter" (EPA-450/4-84-007p) (U. S. Environmental Protection Agency, 1987).

Sampling Method

Sample Collection-

Collection of POM material from stationary sources is generally achieved by using a sampling system that captures both particulate and condensables (Burlingame et al., 1981; Sonnichsen, 1983; DeAngelis et al., 1980; Cottone, 1985). The most prevalent method is the modified Method 5 sampling train equipped with a sorbent resin for collection of condensables. Another method, the Source Assessment Sampling System (SASS), a high volume variation of Method 5, has found application when large sample sizes are required. Methods which are not specifically designed to optimize collection of condensables have also been used and are reported in the literature (Jones et al., 1977). A brief description of the modified Method 5 and the SASS trains is provided. General characteristics of each method are compared in Table 5-3. A detailed procedures manual describing each of these methods is available in a separate report (Schlickenrieder et al., 1984).

Modified Method 5 (MM5). The MM5 sampling train (shown in Figure 5-3 with a sorbent resin trap) is an adaptation of the EPA Method 5 train commonly used in measuring particulate emissions. The modifications are the addition of a

TABLE 5-3. COMPARISON OF MODIFIED METHOD 5 TRAIN/SASS CHARACTERISTICS

Characteristic	MM5 Train	SASS
Inert materials of construction	Yes	No
Percent isokinecity achievable	90 - 110	70 - 150[a]
Typically used to traverse	Yes	No
Particle-sizing of sample	No	Yes
Sample size over a 4-6 hour period (dscm)	3	30
Sampling flow rate (dscmm)	0.02 - 0.03	0.09 - 0.14

[a] Assuming reasonably uniform, nonstratified flow.

Source: Schlickenrieder et al., 1984.

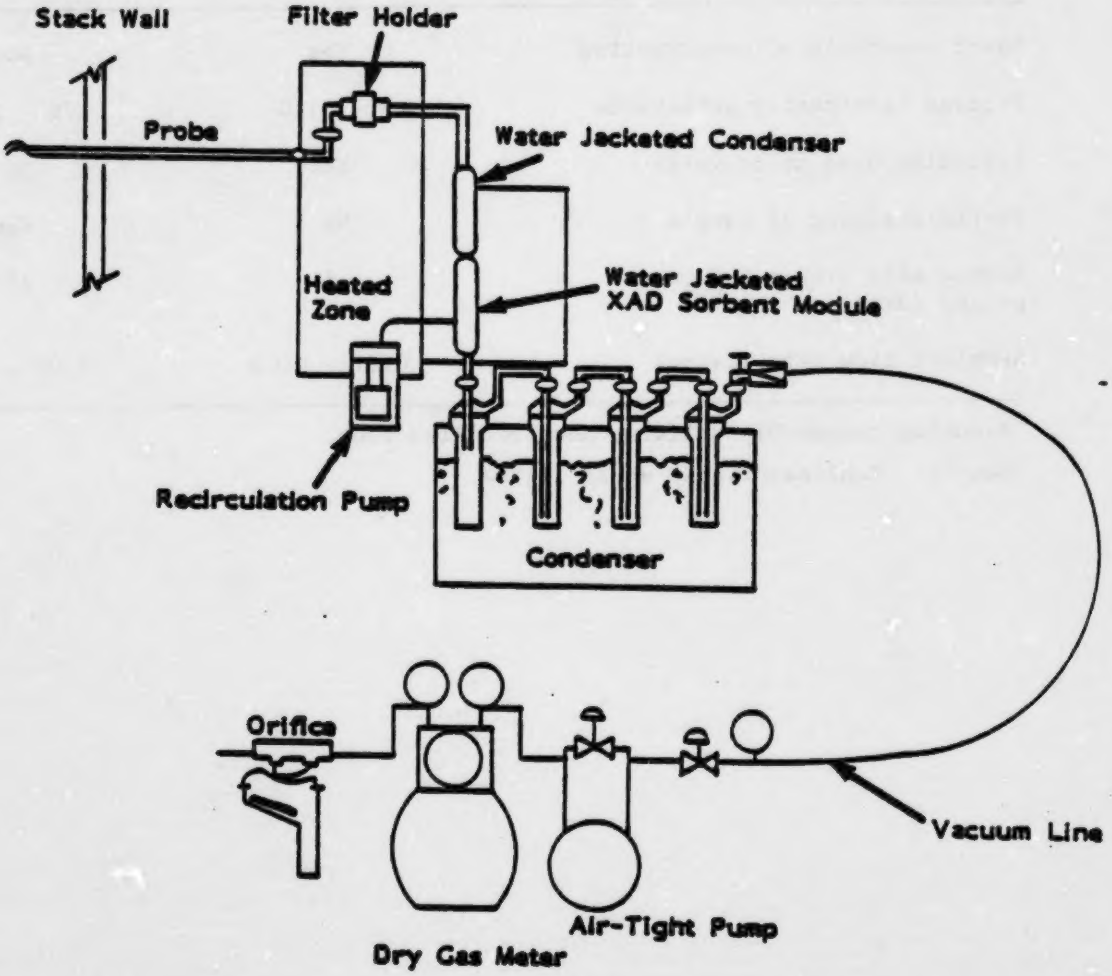

Stack Wall
Filter Holder
Probe
Water Jacketed Condenser
Heated Zone
Water Jacketed XAD Sorbent Module
Recirculation Pump
Condenser
Orifice
Vacuum Line
Air-Tight Pump
Dry Gas Meter

Figure 5-3. Schematic of a Modified Method 5 Sampling Train with a Sorbent Resin Trap

condensor and a sorbent module between the filter and the impingers. The condensor cools the gas stream leaving the filter and conditions the streams prior to entering the sorbent module. The sorbent module contains a polymer resin designed to adsorb a broad range of volatile organic species. A variety of resins have been used including Tenax, Chromsorb 102, and XAD-2, with XAD-2 being the most widely recommended for vapor phase organic compounds including POM. After the sorbent trap, the sample gas is routed through impingers, a pump, and a dry gas meter. The MM5 train is designed to operate at flow rates of approximately 0.015 dscmm (0.5 dscfm) over a 4 hour sampling period. Sample volumes of 3 dscm (100 dscf) are typical.

A major advantage of the MM5 train is that the method provides both a quantitative sample of POM analysis and a determination of particulate loading (front-half filterable particulates) comparable to EPA Method 5. A disadvantage is that large sampling periods are required to collect enough sample to support chemical analysis.

Source Assessment Sampling System (SASS). The SASS train (shown in Figure 5-4) is a multi-component sampling system designed for the collection of particulate, volatile organics, and trace metals (Lentzen et al., 1978). Three heated cyclones and a heated filter allow size fractionation of the particulate sample. Volatile organic material is collected in a sorbent trap containing XAD-2 resin. Volatile inorganic species are collected in a series of impingers before the sample gas exits the system through a pump and a dry gas meter. Large sample volumes are required to ensure adequate recovery of sample fractions. The system is designed to operate at a flow rate of 0.113 scmm (4.0 scfm). Sample volumes of 30 dscm (1000 dscf) are typical.

An advantage of the SASS train is that the sample is collected in a manner that allows a determination of the amount of POM associated with each of the particle size fractions. Another advantage is the large quantity of sample collected, which makes SASS the sampler of choice when a large variety of chemical and bioassay analyses are desired. A disadvantage to using the SASS train is that the system is not designed to have the ability to traverse the stack. Also, the need for constant flow to assure proper

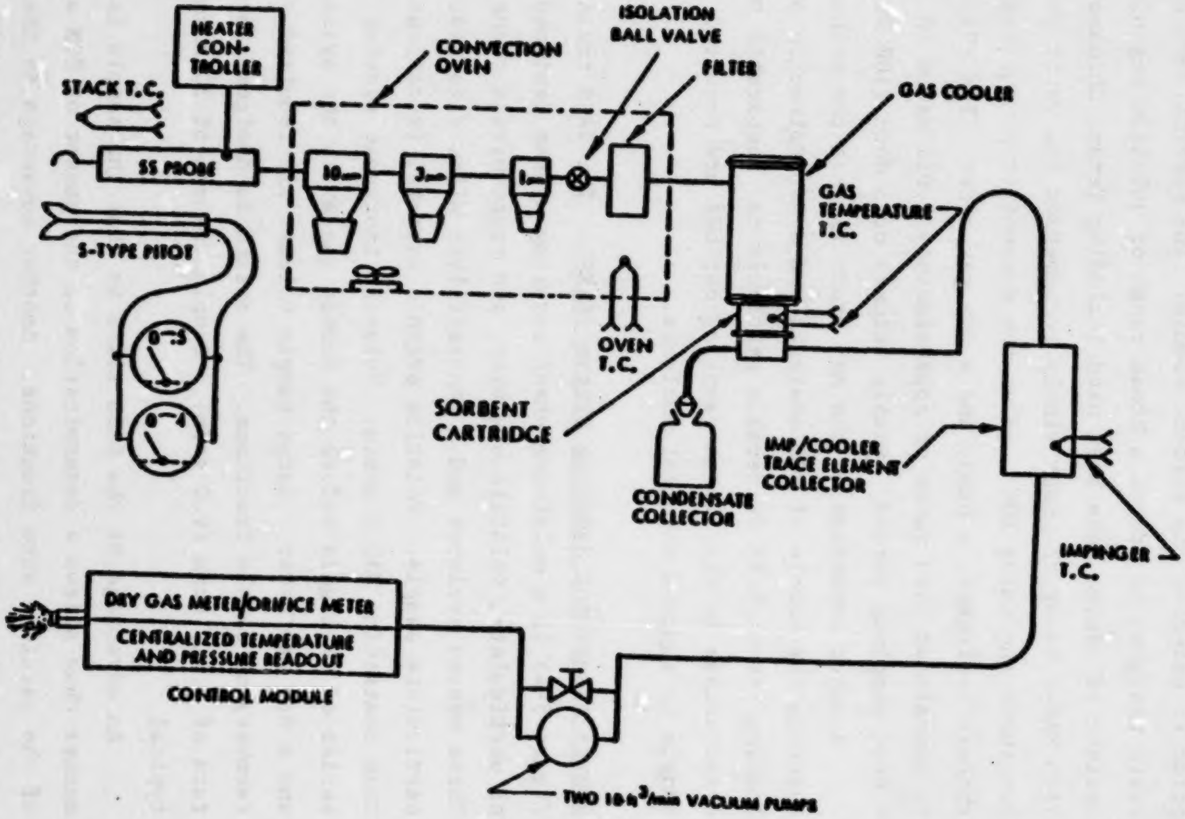

HEATER CON-TROLLER
STACK T.C.
SS PROBE
S-TYPE PITOT
0-.5
0-4
CONVECTION OVEN
10µm
3µm
1µm
ISOLATION BALL VALVE
FILTER
OVEN T.C.
GAS COOLER
GAS TEMPERATURE T.C.
SORBENT CARTRIDGE
CONDENSATE COLLECTOR
IMP/COOLER TRACE ELEMENT COLLECTOR
IMPINGER T.C.
DRY GAS METER/ORIFICE METER
CENTRALIZED TEMPERATURE AND PRESSURE READOUT
CONTROL MODULE
TWO 10-ft³/min VACUUM PUMPS

Figure 5-4. Schematic of a SASS Sampling Train

size fractionation renders the SASS train less amenable for compliance determination since isokinetic conditions are not achieved. Isokinetic conditions can be maintained at the sacrifice of particle sizing capability. Another drawback includes potential corrosion of the stainless steel components of the SASS train by acidic stack gases.

Sample Recovery-

Quantitative recovery of POM requires the separation of POM from the remainder of the collected material, as well as efficient removal from collection media. Solvent extraction techniques which are commonly used for recovery of POM from filters, adsorbent, and liquid media are briefly described.

Soxhlet. Soxhlet extraction is generally recognized as the standard method for preparing a POM-containing solvent extract of solid matrices (Griest and Caton, 1983). This technique is applicable for the extraction of POM from both filter and sorbent catches. This procedure has been specified as a standard reference for extraction of POM by the American Society for Testing Materials, the U. S. Intersociety Committee on Recommended Methods, and the U. S. Environmental Protection Agency's Procedures Manual for Level 1 Environmental Assessment (Griest and Caton, 1983).

Filter samples are folded and placed directly in the extraction chamber of the soxhlet. Polymeric resins are typically transferred to cellulose or glass extraction thimbles and then placed in the soxhlet for extraction. Recommended solvents and extraction periods vary depending on the sample matrix and the collection media (Griest and Caton, 1983; Lee and Schuetzle, 1985). Typical solvents used for extraction of POM from filters, include methylene chloride, cyclohexane, or benzene (Schlickenrieder et al., 1984; Lee and Schuetzle, 1985; Lee et al., 1979; Griest and Caton, 1983). Some investigators recommend an initial extraction with methylene chloride followed by subsequent extraction with a more polar solvent such as methanol (Jones et al., 1977). Solvents for extraction of polymeric resins are typically chosen based on the nature of the adsorbent. Methylene chloride followed by methanol is commonly selected for extracting POM from XAD-2 and Chromsorb 102 resins. Hydrocarbons, such as pentane followed by methanol, have been recommended for extracting Tenax (Jones et al., 1977).

Sonication. Ultrasonic agitation or sonication uses high intensity ultrasonic vibration (~20 KHz) to enhance solvent sample contact. Extractions involve the insertion of a sonication probe into the sample-containing extraction vessel, or a sonication bath in which the sample-containing extraction vessel is set. Filter samples are typically shredded and placed in a glass extraction vessel along with solvents. Sonication is typically carried out for periods ranging from a few minutes to one hour (Griest and Caton, 1983). Extracted POM are then separated from insoluble materials using conventional filtration techniques. Table 5-4 lists reported ultrasonic agitation recoveries of POM from air particulate and coal fly ash using a range of extraction periods and solvents (Griest and Caton, 1983). Recommended solvents include cyclohexane, benzene, acetonitrile, tetrahydrofuran, and methylene chloride (Griest and Caton, 1983).

Solvent Partitioning. Solvent partitioning, or liquid-liquid extraction is the traditional procedure for extraction from liquid sample matrices (Lentzen et al., 1978; Griest and Caton, 1983). The extraction is typically performed in a separatory funnel by agitation and shaking the sample-containing liquid with a suitable solvent. Reported solvents include methylene chloride and cyclohexane (Griest and Caton, 1983).

Analytical Method

A variety of analytical techniques have been used to quantify the POM content of complex environmental samples. This section presents a brief overview of the most commonly used techniques.

TABLE 5-4. RECOVERIES OF POM FROM AIR PARTICULATE AND COAL FLY ASH BY ULTRASONIC EXTRACTION

Sample Matrix	POM[a]	Level[b]	Percentage Recovery	Extraction Conditions	
				Solvent[c]	Time
Air particulates	Anthr	35 mg	95	CH	8 min x 2
	Phen	147 ng	97.5		
	BaP	355 ng	98.2		
	BaP	---	≥90	AN	5 min
	BaP	10 ug	46.5	B	5 min x 1
			70.4		5 min x 2
			83.1		5 min x 3
			91.0		5 min x 4
	BaP	200 ng	99.8	THF	10 min
	BaP	10 - 30 ug	96.6	CH	30 min x 1
			3.1		30 min x 2
			96.8		60 min x 1
			2.6		60 min x 2
Coal fly ash	BaP	100 ng/g	25.2	B	30 sec x 2

[a] Anthr = anthracene; BaP = benzo(a)pyrene; Phen = phenanthrene.

[b] Amount or concentration of POM in Recovery Study.

[c] AN = acetonitrile; CH = cyclohexane; B = benzene; THF = tetrahydrofuran.

High Performance Liquid Chromatography (HPLC)-

The use of liquid chromatography for the determination of specific POM compounds in complex environmental samples has increases significantly in recent years. Detailed reviews are available in the literature that describe various modes of separation, and applications of liquid chromatography (LC) in the measurement of POM (Dong et al., 1982; Wise, 1985; May and Wise, 1985; Zelenski et al., 1980b; Vandemark et al., 1982; James et al., 1985; Wise, 1983; Federal Register, 1984). Although not offering the high separation efficiency of capillary Gas Chromatography (GC), HPLC offers three distinct advantages for POM analysis. First, HPLC offers a variety of stationary and mobile phases which provide selectivity for the separation of POM isomers not generally separated by GC. Second, HPLC coupled with a fluorescence detector provides both sensitivity and selectivity. Individual POM compounds have characteristic fluorescence excitation and emission spectra. Finally, HPLC is an extremely useful fractionation technique for the isolation of POM for subsequent analysis by other chromatographic or spectroscopic techniques.

Gas Chromatography (GC)-

Several studies have been performed using gas chromatography for the separation and determination of POM in environmental samples. Detailed reviews are available in the literature that describe various applications of GC (Bartle, 1985; Federal Register, 1984; Chuang and Petersen, 1985).

The most frequently used detector for GC analysis of POM is the flame ionization detector (FID). Its general response character makes it ideal for several classes of compounds, but necessitates an extensive clean-up procedure prior to GC to eliminate possible interfering compounds. The advantages of using FID include linear response, sensitivity, and day-to-day quantitative reliability to routine determinations. Typical detection limits are below 1 ng.

Numerous applications using the combination of Gas Chromatography and Mass Spectrometry (GC/MS) are also described. EPA Methods 625 and 1625 are both GC/MS techniques for the determination of POM compounds (Federal Register, 1984). Advantages of GC/MS techniques include a high level of sensitivity for trace level detection, versatility for the separation of a large number of compounds, and specificity for absolute identification. The marked disadvantage is that is is significantly more expensive than other techniques.

FORMALDEHYDE

There is no EPA Reference Method for source sampling and analysis of formaldehyde. The procedures described here were extracted from the EPA report "Locating and Estimating Air Emissions from Sources of Formaldehyde" (EPA-450/4-84-007e) (U. S. Environmental Protection Agency, 1984b). Though no reference method exists, EPA has published a recommended sampling and analysis procedure for aldehydes in general that includes formaldehyde (Thrun et al., 1981; Harris et al., 1979). This method involves the reaction of formaldehyde with 2,4-dinitrophenylhydrazine (DNPH) in hydrochloric acid (HCl) to form 2,4-dinitrophenylhydrazone. The hydrazone is then analyzed by high performance liquid chromatography (HPLC).

Exhaust containing formaldehyde is passed through a modified Method 5 system with impingers or bubblers containing DNPH in 2N HCl (Figure 5-5). The molar quantity of DNPH in the impingers must be in excess of the total molar quantity of aldehydes and ketones in the volume of gas sampled. Formaldehyde, higher molecular weight aldehydes, and ketones in the gas react with DNPH to yield hydrazone derivatives, which are extracted from the aqueous sample with chloroform. The chloroform extract is washed with 2N HCl followed by distilled water, and is then evaporated to dryness. The residue is dissolved in acetonitrile. The solution is then analyzed by HPLC with an ultraviolet (UV) detector set at a wavelength of 254 microns. The mobile phase is 62 percent acetonitrile/38 percent water. The recommended column is a 4.6 mm by 25 cm stainless steel 5 micron Zorbax ODS (Dupont) reverse phase column, and the flow rate is 1.5 ml/min. Under the above conditions, the residence time of formaldehyde is 4.46 minutes. The detection limit of the method is 0.1 ng to 0.5 ng. Aldehydes have been recovered from air sample spikes with an average efficiency of 96 percent (±5.5 percent) (Thrun et al., 1981).

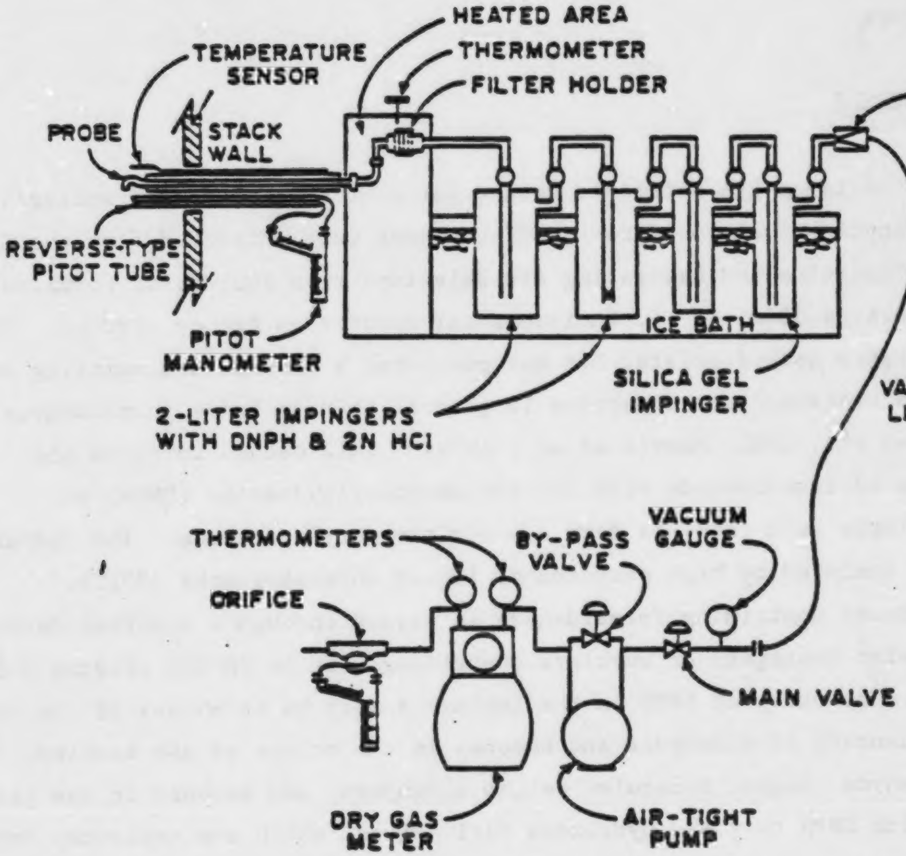

HEATED AREA
TEMPERATURE SENSOR
THERMOMETER
FILTER HOLDER
CHECK VALVE
PROBE
STACK WALL
REVERSE-TYPE PITOT TUBE
PITOT MANOMETER
ICE BATH
SILICA GEL IMPINGER
VACUUM LINE
2-LITER IMPINGERS WITH DNPH & 2N HCl
VACUUM GAUGE
THERMOMETERS
BY-PASS VALVE
ORIFICE
MAIN VALVE
DRY GAS METER
AIR-TIGHT PUMP

Figure 5-5. Method 5 Sampling Train Modified for the Measurement of Formaldehyde

Modifications of this general method have been applied for low level ambient air measurements of formaldehyde. In estimating low levels by this procedure, precautions must be taken to insure that degradation of the absorbing reagent does not occur. One measure found to be helpful consists of conditioning the glass samplers by rinsing them with dilute sulfuric acid followed by rinsing with the 2,4-DNPH absorbing solution (Elia, 1983).

Because higher molecular weight aldehydes and ketones also react with DNPH, they may interfere with the analysis of formaldehyde at some chromatographic conditions. Thus, it may be necessary to adjust the chromatographic conditions in order to give adequate separation of the formaldehyde-DNPH derivative (2,4-dinitrophenylhydrazone) from the hydrazone derivatives formed by higher molecular weight aldehydes and ketones. It may also be necessary to adjust the acetonitrile/water ratio to avoid interference with residual DNPH.

When sulfur dioxide is present in the emission stream, it can dissolve in the absorbing solution to produce sulfite ion, which reacts rapidly with formaldehyde to form bisulfite. This side reaction should not be a problem as long as the absorbing solution is kept acidic (pH < 3). However, the effect of high sulfur dioxide concentrations on the accuracy of the method has not been tested (Elia, 1983).

It should be noted that unpredictable deterioration has been observed for some samples analyzed by this method. Samples should therefore be analyzed within a few hours after collection (Elia, 1983). Finally, the method does not apply when formaldehyde is contained in particulate matter.

RADIONUCLIDES

There is no EPA Reference Method for source sampling radionuclide emissions. However, information on testing radionuclide emissions from combustion sources, principally coal-fired utility and industrial boilers, is available from EPA's previous National Emission Standards for Hazardous Air Pollutant (NESHAP) development program for radionuclides. Radionuclide test reports indicate that the general testing procedure involves sampling the source for particulate matter emissions using either an EPA Method 5 train or a SASS train (as described earlier in this section) and having the collected particulate matter analyzed for radiochemical activity (Roeck et al., 1983; Roberson and Eggleston, 1983).

Generally, the SASS or Method 5 trains are operated according to their specified procedures. The one consideration which was brought out was that the sampling must produce a minimum mass of sample to satisfy the requirements for a valid radioassay. The minimum mass requirement was found to range from 200 mg to 4 g depending on the analytical laboratory and their types of equipment. Based on available data, a minimum sample size of 500 mg was established (Roberson and Eggleston, 1983). Since it inherently collects a larger volume of sample, a SASS train may be preferred over Method 5 for radionuclide emissions testing.

Radiochemical analysis procedures include basic chemistry techniques such as drying, ashing, total sample dissolution, and sequential separation. Individual isotopes are measured for radioactivity concentration using high sensitivity instrumentation. Radiochemical techniques are traced gravimetrically of radioactively, as appropriate, to the species analyzed. Isotopic identification methods include utilization of parent-daughter growth/decay characteristics and/or characteristic alpha energy identification such that reported isotopes are specifically determined. Also, to maximize analytical sensitivity, all techniques are applied in a manner that uses the entire sample mass (Roberson and Eggleston, 1983).

SECTION 6

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APPENDIX A
DATA BASE DEVELOPMENT

The coal and oil combustion toxic pollutant emissions data base for the report "Summary of Trace Emissions From and Recommendations of Risk Assessment Methodologies for Coal and Oil Combustion Sources" was developed through manual and computerized literature searching and through telephone contacts with individuals knowledgeable in the areas of combustion sources and toxic emissions from combustion. The literature search effort consisted of searching the Radian library and relevant company project files for combustion source toxic emissions data that either were developed by the company or were obtained through projects related to this topic, and searching computerized data bases of the Dialog® information system. The in-house search proved successful in that approximately 100 documents were identified as potentially being useful to the objectives of the project. These were obtained and evaluated.

The Dialog® search consisted of searching nine data bases that were identified as having the highest probability of containing information relating to combustion source trace emissions and risk assessment methodologies. These data bases, the dates back to which each was searched, and any exclusions/restrictions applied to a data base search are summarized in Table A-1.

The computerized search of these nine data bases identified 1,808 citations that potentially could be useful to the objectives of the project. Abstracts of these 1,808 citations were evaluated and a list of 506 citations were specified from this review that appeared to warrant a full review to extract their toxic emissions data. During the review of the abstracts, approximately 240 references were discounted on the basis of being of only marginally applicable or of containing data that applies to foreign sources. References containing emissions data on combustion sources located outside the United States were specified by EPA to not be obtained. Another 105 were discarded on the basis that they were exact duplicates with

TABLE A-1. DATA BASES SEARCHED IN THE DIALOG® SYSTEM

Data Base	Dates Searched	Restrictions
Chemical Abstracts (CA) Search	1972 - 1985	a
NTIS	1964 - 1985	a
Compendex	1970 - 1985	a
DOE Energy	1974 - 1985	a
Electric Power Database	1972 - 1985	a
Pollution Abstracts	1970 - 1985	a
Environmental Bibliography	1974 - 1985	a
Enviroline	1970 - 1985	a
Federal Research in Progress	Current	a

[a] Limited to references available in English; all patent literature was excluded.

a reference previously identified or they were duplicates of work that had been published or presented in another source. In total, 161 references were obtained from the computerized literature search and evaluated for this study.

The final source of data for the project was the Emissions Assessment Data System (EADS) which is maintained by the Air and Energy Engineering Research Laboratory (AEERL) of the U. S. EPA at Research Triangle Park, North Carolina. The EADS contained computerized summaries of 197 reports of tested trace metal emissions from combustion sources. Upon a review of the summaries, most of the test reports were found to be duplicates of references previously identified and analyzed or were not directly applicable for reasons of being concerned with wood or organic waste fuels and unapplicable sources such as internal combustion engines.

APPENDIX B

FUEL HEATING VALUES

The information presented in this appendix on fuel heating values is intended to supplement the emission factors provided in Section 4 in the calculation of toxic emissions for a combustion source. Fuel heating values are useful in calculating toxic pollutant emissions when available emission factors are expressed in terms of mass of emissions/mass of fuel burned (e.g., lb As/ton coal) and only the source's total energy input level (10^6 Btu/yr) is known or when the emission factor is expressed in terms of mass of emissions/unit heat energy input (lb Ni/10^6 Btu) and only the total quantity of fuel burned (tons/yr) is known. Heating content values are provided in this appendix for coal and oil fuels.

Coal is a general term used to describe a wide range of materials that are burned to produce heat, which in turn in some combustion sectors, is used to generate energy. Four recognized classes containing a total of 13 component groups are used to classify different types of coal. The parameters predominantly used to classify coals are:

- the amount of volatile matter contained in the coal;
- the amount of fixed carbon contained in the coal;
- the amount of inherent moisture contained in the coal; and
- the amount of oxygen contained in the coal.

The four coal classes and their component groups are presented in Table B-1 (Babcock and Wilcox, 1978; Singer, 1981). Typical heating values of domestic coals are illustrated in Table B-2. Mean heating values, by coal group, based on the data in Table B-2 are given below.

Meta-anthracite - 11,029 Btu/lb
Anthracite - 13,061 Btu/lb
Semianthracite - 12,857 Btu/lb

TABLE B-1. CLASSIFICATION OF COALS

Coal Class	Component Groups
I. Anthracitic	1. Meta-anthracite 2. Anthracite 3. Semianthracite
II. Bituminous	1. Low volatile bituminous 2. Medium volatile bituminous 3. High volatile A bituminous 4. High volatile B bituminous 5. High volatile C bituminous
III. Subbituminous	1. Subbituminous A 2. Subbituminous B 3. Subbituminous C
IV. Lignitic	1. Lignite A 2. Lignite B

Sources: Babcock and Wilcox (1978); Singer (1981).

TABLE B-2. TYPICAL HEATING VALUES OF UNITED STATES' COALS

COAL CLASS	COMPONENT GROUP	COAL SOURCE		HEATING VALUE Btu/lb
Anthracitic	A1	PA		12,745
	A1	RI		9,313
			Group Average	11,029
	A2	PA		12,925
	A2	PA		11,950
	A2	PA		13,540
	A2	PA		12,820
	A2	PA		13,130
	A2	CO		13,720
	A2	NM		13,340
			Group Average	13,061
	A3	AR		13,360
	A3	VA		11,925
	A3	AR		13,700
	A3	PA		13,450
	A3	VA		11,850
			Group Average	12,857
			Class Average	12,698
Bituminous	B1	AR		13,700
	B1	MD		13,870
	B1	OK		13,800
	B1	WV		14,730
	B1	WV		14,715

TABLE B-2. TYPICAL HEATING VALUES OF UNITED STATES' COALS (Continued)

COAL CLASS	COMPONENT GROUP	COAL SOURCE		HEATING VALUE Btu/lb
	B1	PA		13,800
	B1	MD		13,220
			Group Average	13,976
	B2	PA		14,310
	B2	PA		14,030
	B2	VA		13,720
	B2	PA		13,800
	B2	AL		13,530
			Group Average	13,878
	B3	KY		14,090
	B3	KY		14,480
	B3	OH		12,850
	B3	PA		13,325
	B3	AL		14,210
	B3	CO		13,210
	B3	KS		12,670
	B3	KY		14,290
	B3	MO		12,990
	B3	NM		12,650
	B3	OH		12,990
	B3	OK		13,630
	B3	PA		13,610
	B3	TN		13,890
	B3	TX		12,230
	B3	UT		12,990

TABLE B-2. TYPICAL HEATING VALUES OF UNITED STATES' COALS (Continued)

COAL CLASS	COMPONENT GROUP	COAL SOURCE		HEATING VALUE Btu/lb
	B3	VA		14,510
	B3	WA		12,610
	B3	WV		14,350
			Group Average	13,451
	B4	OH		13,150
	B4	IL		11,910
	B4	UT		12,600
	B4	IL		12,130
	B4	KY		12,080
	B4	MO		11,300
	B4	OH		12,160
	B4	WY		12,960
			Group Average	12,286
	B5	IL		11,340
	B5	IL		10,550
	B5	IL		11,480
	B5	IN		11,420
	B5	IA		10,720
	B5	MI		11,860
			Group Average	11,228
			Class Average	13,077
Subbituminous	S1	MT		11,140
	S1	WA		10,330
			Group Average	10,735

TABLE B-2. TYPICAL HEATING VALUES OF UNITED STATES' COALS (Continued)

COAL CLASS	COMPONENT GROUP	COAL SOURCE		HEATING VALUE Btu/lb
	S2	WY		9,345
	S2	WY		9,610
			Group Average	9,478
	S3	CO		8,580
	S3	WY		8,320
			Group Average	8,450
			Class Average	9,554
Lignitic	L1	ND		7,255
	L1	ND		7,210
	L1	TX		7,350
	L1	ND		6,960
			Group Average	7,194

A1 = Meta-anthracite
A2 = Anthracite
A3 = Semianthracite
B1 = Low volatile bituminous
B2 = Medium volatile bituminous
B3 = High volatile A bituminous
B4 = High volatile B bituminous
B5 = High volatile C bituminous
S1 = Subbituminous A
S2 = Subbituminous B
S3 = Subbituminous C
L1 = Lignite A

Source: Singer (1981); Parker (1981); Babcock and Wilcox (1978).

Low volatile bituminous - 13,976 Btu/lb
Medium volatile bituminous - 13,878 Btu/lb
High volatile A bituminous - 13,451 Btu/lb
High volatile B bituminous - 12,286 Btu/lb
High volatile C bituminous - 11,228 Btu/lb
Subbituminous A - 10,735 Btu/lb
Subbituminous B - 9,478 Btu/lb
Subbituminous C - 8,450 Btu/lb
Lignite A - 7,194 Btu/lb

The mean heating value of each major class of coal, calculated from the data in Table B-2, is as follows.

Anthracitic - 12,698 Btu/lb
Bituminous - 13,077 Btu/lb
Subbituminous - 9,554 Btu/lb
Lignitic - 7,194 Btu/lb (lignite A only)

More information on coal heating values, expressed by the geographical source of the coal, is provided in Table B-3.

The heating value of coal, like the trace metal content, varies between coal regions, between mines within a region, between seams within a mine, and within a seam. The variability is minimal compared to that found with trace metal levels, but nevertheless it may be important when attempting to use fuel heat content as a factor in source emission calculations. Data presented in Table B-4 illustrate coal heat content variability. Heat content among coals from several different mines within a region appears to exhibit greater variability than either variability within a mine or within a seam. For the sample points in Table B-4, intermine variability averaged 15 percent, intramine variability 7 percent, and intraseam variability 3 percent. Since few combustion sources burn coal from just one seam or one mine, coal heat content variability may significantly affect emissions estimates that are being calculated using emission factors, coal use data, and coal heat content data, even if the source gets all its coal from the same area of the country.

TABLE B-3. MEAN COAL HEATING VALUES BY GEOGRAPHIC REGION

Region	Heating Value, Btu/lb
Northern Appalachia	
Maryland	11,344
Pennsylvania	11,825
Ohio	10,909
Northern West Virginia	11,975
Central Appalachia	
Eastern Kentucky	11,326
Virginia	11,802
Southern West Virginia	11,975
Central	
Indiana	10,811
Illinois	10,710
Western Kentucky	11,326
Northwest (Powder River Basin)	
Montana	8,987
Wyoming	9,169
Southwest	
New Mexico	8,966

Source: U. S. National Committee for Geochemistry (1980).

TABLE B-4. EXAMPLES OF COAL HEAT CONTENT VARIABILITY

	COAL SOURCE	COAL HEAT CONTENT, Btu/lb		STANDARD DEVIATION	PERCENT VARIANCE ABOUT THE MEAN
		MEAN	RANGE		
Intermine Variability	Eastern U. S.	12,320	10,750 - 13,891	NA[a]	12.7
	Central U. S.	10,772	9,147 - 12,397	NA	15
	Western U. S.	11,227	9,317 - 13,134	NA	17
Intramine Variability	Eastern U. S.	12,950	NA	624	4.8
		10,008	9,182 - 10,834	NA	8.0
		12,000	11,335 - 12,665	NA	5.5
	Central U. S.	12,480	NA	708	5.7
		10,975	9,667 - 12,284	NA	12.0
	Western U. S.	10,351	9,791 - 10,911	NA	5.4
Intraseam Variability	Eastern U. S.	12,230	NA	371	3.0
	Central U. S.	10,709	10,304 - 11,113	NA	3.7
	Western U. S.	11,540	NA	291	2.5

[a] NA = Not Available.

Source: Pedco Environmental (1982); U. S. Environmental Protection Agency (1977); U. S. Environmental Protection Agency (1978); U. S. Environmental Protection Agency (1980a).

The term fuel oil is conveniently applied to cover a wide range of petroleum products, including crude petroleum, lighter petroleum fractions such as kerosene, and heavier residual fractions left after distillation. To provide standardization and a means for comparison, specifications have been established that separate fuel oils into various grades. Fuel oils are graded according to specific gravity and viscosity, with No. 1 Grade being the lightest and No. 6 the heaviest. The heating value of fuel oils is expressed in terms of Btu/gal of oil at 16°C (60°F) or Btu/lb of oil. The heating value per gallon increases with specific gravity because there is more weight per gallon. The heating value per pound of oil varies inversely with specific gravity because lighter oil contains more hydrogen.

For an uncracked distillate or residual oil, heating value can be approximated by the following equation.

$$\text{Btu/lb} = 17{,}660 + (69 \times \text{API gravity})$$

For a cracked distillate, the relationship becomes,

$$\text{Btu/lb} = 17{,}780 + (54 \times \text{API gravity}).$$

Typical heating values of predominantly used fuel oils are presented in Tables B-5 and B-6 through B-10. Tables B-6 to B-10 represent a summary of an extensive assessment of fuel oils that has been conducted by the U. S. Department of Energy's Bartlesville Energy Technology Center. Figure B-1 provides a key to the fuel oil regions as presented in Tables B-6 to B-10.

TABLE B-5. TYPICAL HEATING VALUES OF FUEL OILS

	FUEL OIL GRADES				
	No. 1	No. 2	No. 4	No. 5	No. 6
Type	Distillate	Distillate	Very Light Residual	Light Residual	Residual
Color	Light	Amber	Black	Black	Black
Heating Value[a]					
Btu/gal	137,000	141,000	146,000	148,000	150,000
Btu/lb	19,670 - 19,860	19,170 - 19,750	18,280 - 19,400	18,100 - 19,020	17,410 - 18,900

[a] The samples analyzed for Btu/gal and Btu/lb heating values are different; therefore, the heating values presented do not directly correspond to one another.

Source: Babcock and Wilcox (1978); Singer (1981).

TABLE B-6. TYPICAL HEATING VALUES FOR OILS CONSUMED IN THE EASTERN REGION[a]

FUEL OIL GRADE	NUMBER OF SAMPLES ANALYZED	HEATING VALUE, Btu/gal	
		RANGE	MEAN
No. 1	33	132,500 - 135,700	134,200
No. 2	56	133,100 - 146,600	139,500
No. 4	1	-	146,000
No. 5 (light)	1	-	148,400
No. 5 (heavy)	0	-	-
No. 6	17	147,000 - 157,600	151,900

[a] See Figure B-1 for key to the regions.

Source: Shelton (1982).

TABLE B-7. TYPICAL HEATING VALUES FOR OILS CONSUMED IN THE SOUTHERN REGION[a]

FUEL OIL GRADE	NUMBER OF SAMPLES ANALYZED	HEATING VALUE, Btu/gal RANGE	HEATING VALUE, Btu/gal MEAN
No. 1	13	132,900 - 135,400	134,300
No. 2	19	136,400 - 141,500	139,400
No. 4	0	-	146,000
No. 5 (light)	0	-	148,400
No. 5 (heavy)	0	-	-
No. 6	14	150,500 - 156,500	152,900

[a] See Figure B-1 for key to the regions.

Source: Shelton (1982).

TABLE B-8. TYPICAL HEATING VALUES FOR OILS CONSUMED IN THE CENTRAL REGION[a]

FUEL OIL GRADE	NUMBER OF SAMPLES ANALYZED	HEATING VALUE, Btu/gal	
		RANGE	MEAN
No. 1	27	132,500 - 135,700	134,000
No. 2	35	135,900 - 146,600	139,200
No. 4	2	146,000 - 150,100	148,050
No. 5 (light)	4	148,400 - 151,500	149,900
No. 5 (heavy)	0	-	-
No. 6	10	150,600 - 158,900	152,900

[a] See Figure B-1 for key to the regions.

Source: Shelton (1982).

TABLE B-9. TYPICAL HEATING VALUES FOR OILS CONSUMED IN THE ROCKY MOUNTAIN REGION[a]

FUEL OIL GRADE	NUMBER OF SAMPLES ANALYZED	HEATING VALUE, Btu/gal	
		RANGE	MEAN
No. 1	14	133,100 - 135,100	134,200
No. 2	17	136,100 - 140,400	139,000
No. 4	2	150,100 - 150,500	150,300
No. 5 (light)	2	153,900 - 156,500	155,200
No. 5 (heavy)	1	-	150,000
No. 6	7	151,900 - 159,200	154,600

[a] See Figure B-1 for key to the regions.

Source: Shelton (1982).

TABLE B-10. TYPICAL HEATING VALUES FOR OILS CONSUMED IN THE WESTERN REGION[a]

FUEL OIL GRADE	NUMBER OF SAMPLES ANALYZED	HEATING VALUE, Btu/gal RANGE	HEATING VALUE, Btu/gal MEAN
No. 1	16	131,700 - 136,200	134,600
No. 2	18	136,100 - 140,500	139,000
No. 4	0	-	-
No. 5 (light)	0	-	-
No. 5 (heavy)	1	-	152,100
No. 6	12	149,900 - 163,500	154,400

[a] See Figure B-1 for key to the regions.

Source: Shelton (1982).

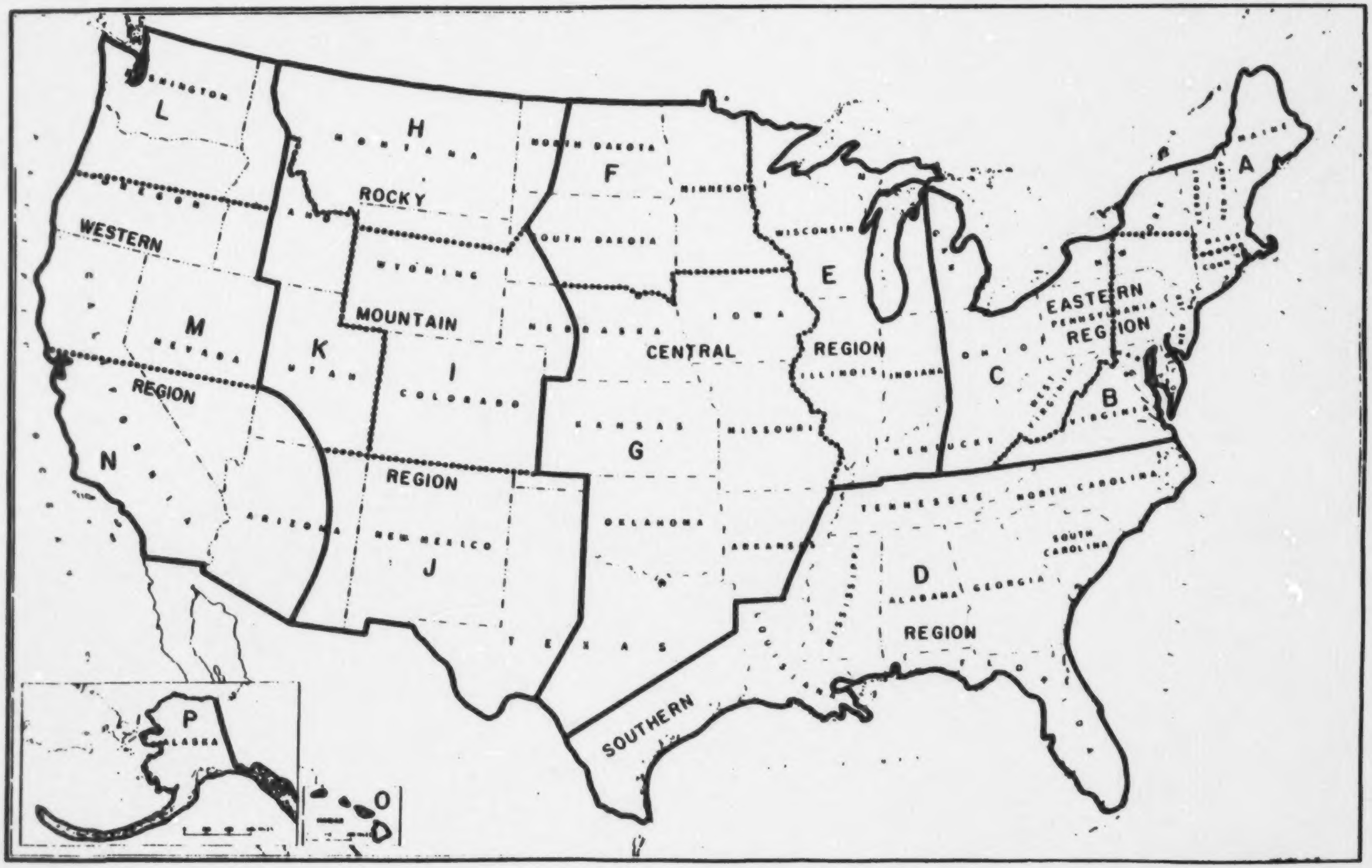
A
EASTERN REGION
PENNSYLVANIA
B
VIRGINIA
C
OHIO
KENTUCKY
NORTH CAROLINA
SOUTH CAROLINA
TENNESSEE
D
REGION
ALABAMA
GEORGIA
MISSISSIPPI
LOUISIANA
FLORIDA
E
REGION
WISCONSIN
ILLINOIS
INDIANA
F
NORTH DAKOTA
SOUTH DAKOTA
MINNESOTA
IOWA
NEBRASKA
CENTRAL
MISSOURI
KANSAS
G
OKLAHOMA
ARKANSAS
SOUTHERN
TEXAS
H
MONTANA
ROCKY
WYOMING
MOUNTAIN
I
COLORADO
REGION
NEW MEXICO
J
K
UTAH
L
WASHINGTON
OREGON
WESTERN
M
NEVADA
REGION
N
ARIZONA
P
ALASKA
O

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Figure B-1. Key to the fuel oil regions in Tables B-6 to B-10.

APPENDIX C

EMISSION FACTORS MEASURED AT INDIVIDUAL COAL-FIRED BOILERS

This appendix summarizes the data base for measured emission factors from coal-fired boilers. It was compiled from a review of the literature included in Section 6. The summary tables are organized by pollutant. The tables for the eight trace metals, arranged in alphabetical order, are first. Tables for radionuclides are next, followed by tables for POM. Within each pollutant, tables are organized by combustion sector, coal type, and boiler design. Each table lists the average measured emission factor for each boiler tested. The range of emission factors measured at each boiler is also listed if results of more than one test run were reported. For each test, the tables also list the control status of the boiler, and the reference for the information.

TABLE C-1. MEASURED ARSENIC EMISSION FACTORS FOR UTILITY, BITUMINOUS COAL, PULVERIZED DRY BOTTOM BOILERS

Emission Factor ($lb/10^{12}$ Btu)			
Mean[a]	Range	Control Status	Reference
48.8	---	Mech. Ppt/ESP	Shih *et al.*, 1980b
30.2	---	Mech. Ppt/ESP	Shih *et al.*, 1980b
3.95	---	Wet Scrubber	Shih *et al.*, 1980b
26[b]	---	ESP	Baig *et al.*, 1981
138[c]	62-242	ESP	Evers *et al.*, 1980
886[c]	792-924	Uncontrolled	Evers *et al.*, 1980
54	---	ESP[d]	Sawyer and Higginbotham, 1981a
61	---	ESP[e]	Sawyer and Higginbotham, 1981a
43	---	ESP[e]	Sawyer and Higginbotham, 1981a
820	---	Uncontrolled[d]	Sawyer and Higginbotham, 1981a
910	---	Uncontrolled[e]	Sawyer and Higginbotham, 1981a
500	---	Uncontrolled[e]	Sawyer and Higginbotham, 1981a
68	---	Low Effic. ESP[e]	Higginbotham and Goldberg, 1981
70	---	Low Effic. ESP[e]	Higginbotham and Goldberg, 1981
110	---	Low Effic. ESP[e]	Higginbotham and Goldberg, 1981
430	---	Uncontrolled[d]	Higginbotham and Goldberg, 1981
330	---	Uncontrolled[e]	Higginbotham and Goldberg, 1981
140	---	Uncontrolled[e]	Higginbotham and Goldberg, 1981
620	---	Uncontrolled[e]	Higginbotham and Goldberg, 1981
310	---	Uncontrolled[e]	Higginbotham and Goldberg, 1981
1360	---	Uncontrolled	Scinto *et al.*, 1981
9.4	---	ESP	Scinto *et al.*, 1981
14.9	---	ESP/Scrubber	Scinto *et al.*, 1981
1274[f]	890-1980	Mech. Ppt.	Zielke and Bittman, 1982
192[f]	17-290	Mech. Ppt/1st ESP in Series of 2	Zielke and Bittman, 1982

TABLE C-1. MEASURED ARSENIC EMISSION FACTORS FOR UTILITY, BITUMINOUS COAL, PULVERIZED DRY BOTTOM BOILERS (Continued)

Emission Factor (lb/10^{12} Btu)			
Mean[a]	Range	Control Status	Reference
6.1[g]	<0.29-13.2	Mech. Ppt/2 ESPs in Series	Zielke and Bittman, 1982
31.4	---	Venturi Scrubber	Ondov *et al.*, 1979a
12.2	8.19-24.6	Venturi Scrubber	Ondov *et al.*, 1979a
21.4	---	Venturi Scrubber	Ondov *et al.*, 1979a
0.46[h]	0.35-0.51	ESP	Ondov *et al.*, 1979b
---	13.4-35.5[i]	ESP	Ondov *et al.*, 1979b
64[h]	62-66	Uncontrolled	Cowherd *et al.*, 1975
32[h]	19-49	Mech. Ppt.	Cowherd *et al.*, 1975

---

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Average of tests of six different boilers.

[c] Average of eight tests of the same boiler.

[d] Boiler operating under baseline (design) conditions.

[e] Boiler operating under low-NO_x conditions - certain burners admit only air rather than fuel, or different fuel/air ratios are admitted than under design operating conditions.

[f] Average of seven tests of the same boiler.

[g] Average of five tests of the same boiler.

[h] Average of three tests of the same boiler.

[i] Range for six tests of the same boiler.

TABLE C-2. MEASURED ARSENIC EMISSION FACTORS FOR UTILITY PULVERIZED WET BOTTOM BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Control Status	Reference
15.3	Mech. Ppt/ESP	Shih, *et al.*, 1980b
44.2	ESP	Shih, *et al.*, 1980b
44.2	ESP	Shih, *et al.*, 1980b
76.7	Venturi Scrubber	Shih, *et al.*, 1980b
165	ESP	Shih, *et al.*, 1980b
572	ESP	Shih, *et al.*, 1980b

TABLE C-3. MEASURED ARSENIC EMISSION FACTORS FOR UTILITY CYCLONE BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor (lb/10^{12} Btu)			
Mean	Range	Control Status	Reference
813	---	Wet Scrubber	Shih, et al., 1980b
6.3	---	ESP	Shih, et al., 1980b
11.4	---	ESP	Shih, et al., 1980b
27.9	---	ESP	Shih, et al., 1980b
12.8	---	ESP	Shih, et al., 1980b
310[b]	130-490	Uncontrolled	Klein, et al., 1975b; Lyon, 1977
13.5[b]	12-15	High Efficiency ESP	Klein, et al., 1975b; Lyon, 1977

---

[a] This column gives the arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Averge of two tests of the same boiler.

TABLE C-4. MEASURED ARSENIC EMISSION FACTORS FOR UTILITY STOKER BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Control Status	Reference
0.77	Fabric Filter	Shih, et al., 1980b
5580	Mechanical Ppt.	Shih, et al., 1980b
432	Multiclone	Shih, et al., 1980b

TABLE C-5. MEASURED ARSENIC EMISSION FACTORS FOR UTILITY BOILERS FIRED WITH SUBBITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Boiler Type	Control Status	Reference
860	Cyclone	Uncontrolled	Leavitt, et al., 1979
810	Cyclone	FGD Scrubber	Leavitt, et al., 1979
11	Pulverized	Venturi Scrubber	Radian, 1975
0.17	Pulverized	ESP (hot side)	Radian, 1975
2.4	NR[a]	ESP (cold side)	Mann, et al., 1978
10	NR	ESP (hot side)	Mann, et al., 1978

[a] NR = not reported.

TABLE C-6. MEASURED ARSENIC EMISSION FACTORS FOR UTILITY BOILERS FIRED WITH LIGNITE COAL

Emission Factor ($lb/10^{12}$ Btu)	Boiler Type	Control Status	Reference
397	Pulverized Dry Bottom	Multiclone	Shih *et al.*, 1980b
367	Pulverized Dry Bottom	Multiclone	Shih *et al.*, 1980b
<2.3	Pulverized Dry Bottom	ESP	Shih *et al.*, 1980b
5.8	Cyclone	ESP	Shih *et al.*, 1980b
11.2	Cyclone	ESP/Wet Scrubbers	Schock *et al.*, 1979
270	Cyclone	Multiclone	Radian, 1975
265	Spreader Stoker	Multiclone	Shih *et al.*, 1980b
<5.3	Spreader Stoker	ESP	Shih *et al.*, 1980b

TABLE C-7. MEASURED ARSENIC EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Emission Factor (lb/10^{12} Btu) Mean[a]	Emission Factor (lb/10^{12} Btu) Range	Boiler Type	Control Status	Reference
29[b]	---	Pulverized Dry Bottom	ESP	Baig et al., 1981
15.8	---	Pulverized Dry Bottom	ESP	Suprenant et al., 1980a
7900	---	Pulverized Dry Bottom	Multiclone	Leavitt et al., 1978b; Fischer et al., 1979
214	---	Pulverized Dry Bottom	Multiclone/Scrubber	Leavitt et al., 1978b; Fischer et al., 1979
690[c]	---	Pulverized Dry Bottom	Uncontrolled	McCurley et al., 1979
120[c]	---	Pulverized Dry Bottom	ESP	McCurley et al., 1979
32.5	---	Pulverized Wet Bottom	Multiclone	Suprenant et al., 1980a
53.7	---	Spreader Stoker	Multiclone/ESP	Suprenant et al., 1980a
102	---	Spreader Stoker	Multiclone	Suprenant et al., 1980a
853	---	Spreader Stoker	Multiclone	Suprenant et al., 1980a
0.32[c]	0.27-0.37	Spreader Stoker	Uncontrolled[d]	Burlingame et al., 1981
81[e]	60-93	Spreader Stoker	Uncontrolled[d]	Burlingame et al., 1981
835	---	Spreader Stoker	Uncontrolled[d]	Burlingame et al., 1981
59[c]	35-83	Spreader Stoker	Uncontrolled	Burlingame et al., 1981
70[c]	65-74	Spreader Stoker	Uncontrolled	Burlingame et al., 1981
190[c]	120-260	Spreader Stoker	Uncontrolled	Burlingame et al., 1981
350	---	Overfeed Stoker	Uncontrolled	Burlingame et al., 1981
1300	---	Overfeed Stoker	Uncontrolled	Burlingame et al., 1981

TABLE C-7. MEASURED ARSENIC EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS (Continued)

Emission Factor ($lb/10^{12}$ Btu)				
Mean[a]	Range	Boiler Type	Control Status	Reference
2400[c]	2200-2600	Overfeed Stoker	Uncontrolled	Burlingame _et al._, 1981
60	---	Overfeed Stoker	Uncontrolled	Burlingame _et al._, 1981
395[c]	370-420	Overfeed Stoker	Economizer, Dust Collector	Burlingame _et al._, 1981
740	---	Spreader Stoker	Uncontrolled[f]	Lips and Higginbotham, 1981
35	---	Spreader Stoker	Mechanical Ppt/ESP[f]	Lips and Higginbotham, 1981
490	---	Spreader Stoker	Uncontrolled[g]	Lips and Higginbotham, 1981
31	---	Spreader Stoker	Mechanical Ppt/ESP[g]	Lips and Higginbotham, 1981

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Average for three boilers.

[c] Average of two tests of the same boiler.

[d] Traveling grate spreader stoker with re-injection from the dust collector. Measured upstream of control device.

[e] Average of three tests of the same boiler.

[f] Boiler operated under baseline (design) conditions.

[g] Boiler operated with low excess air level for NO_x control.

TABLE C-8. MEASURED ARSENIC EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Emission Factor ($lb/10^{12}$ Btu)				
Mean[a]	Range	Boiler Type	Control Status	Reference
340[b]	190-490	Spreader Stoker	Uncontrolled[c]	Burlingame *et al.*, 1981
120	---	Spreader Stoker	Uncontrolled[d]	Goldberg and Higginbotham, 1981
3.0	---	Spreader Stoker	Mechanical Ppt/ESP[d]	Goldberg and Higginbotham, 1981
68	---	Spreader Stoker	Uncontrolled[e]	Goldberg and Higginbotham, 1981
5.8	---	Spreader Stoker	Mechanical Ppt/ESP[e]	Goldberg and Higginbotham, 1981

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[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Mean of two tests of the same boiler.

[c] Traveling grate spreader stoker with re-injection from the dust collector. Measured upstream of controls.

[d] Tested while operating under baseline (design) conditions.

[e] Tested while operating under low-NO_x operating conditions - overfire air rate set at maximum level.

TABLE C-9. MEASURED ARSENIC EMISSION FACTORS FOR COMMERCIAL/INSTITUTIONAL COAL-FIRED BOILERS

Emission Factor ($lb/10^{12}$ Btu)	Type of Coal	Boiler Type	Control Status	Reference
4470	Bituminous	Pulverized Dry Bottom	Uncontrolled	Suprenant et al., 1980b
51.1	Bituminous	Pulverized Dry Bottom	Multiclone/Scrubber	Suprenant et al., 1980b
4.2	Bituminous	Underfeed Stoker	Uncontrolled	Suprenant et al., 1980b
11.6	Bituminous	Spreader Stoker	Mechanical Ppt.	Suprenant et al., 1980b
25.6	Bituminous	Overfeed Stoker	Mechanical Ppt.	Suprenant et al., 1980b
5.3	Anthracite	Stoker	Uncontrolled	Suprenant et al., 1980b
235	Anthracite	Stoker	Uncontrolled	Suprenant et al., 1980b
170	Anthracite	Stoker	Uncontrolled	Suprenant et al., 1980b

TABLE C-10. MEASURED ARSENIC EMISSION FACTORS FOR COAL-FIRED RESIDENTIAL FURNACES

Emission Factor (lb/10^{12} Btu)	Coal Type	Furnace Type	Control Status	Reference
31.0	Bituminous	N.R.[a]	Uncontrolled	DeAngelis and Reznik, 1979
77.5	Bituminous	N.R	Uncontrolled	DeAngelis and Reznik, 1979
2400[b]	Bituminous	Warm Air Furnace with Stoker	Uncontrolled	DeAngelis, 1979
¼445[c]	Bituminous-washed	Warm Air Furnace with Stoker	Uncontrolled	DeAngelis, 1979

[a] N.R. = not reported.

[b] Average of two tests of the same boiler.

[c] Average of two tests of the same boiler. Both were less than the detection limit of 445 lb/10^{12} Btu.

TABLE C-11. MEASURED BERYLLIUM EMISSION FACTORS FOR UTILITY PULVERIZED DRY BOTTOM BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)			
Mean[a]	Range	Control Status	Reference
0.11	---	Wet Scrubber	Shih et al., 1980b
0.44	---	Mech. Ppt/ESP	Shih et al., 1980b
<0.11	---	Mech. Ppt/ESP	Shih et al., 1980b
0.60[b]	---	ESP	Baig et al., 1981
0.89[c]	0.62-1.89	ESP	Evers et al., 1980
102[c]	92-114	Uncontrolled	Evers et al., 1980
14	---	ESP[d]	Sawyer and Higginbotham, 1981a
12	---	ESP[e]	Sawyer and Higginbotham, 1981a
9.5	---	ESP[e]	Sawyer and Higginbotham, 1981a
140	---	Uncontrolled[d]	Sawyer and Higginbotham, 1981a
140	---	Uncontrolled[e]	Sawyer and Higginbotham, 1981a
100	---	Uncontrolled[e]	Sawyer and Higginbotham, 1981a
21	---	Low Effic. ESP[d]	Higginbotham and Goldberg, 1981
31	---	Low Effic. ESP[e]	Higginbotham and Goldberg, 1981
32	---	Low Effic. ESP[e]	Higginbotham and Goldberg, 1981
42	---	Uncontrolled[d]	Higginbotham and Goldberg, 1981
45	---	Uncontrolled[e]	Higginbotham and Goldberg, 1981
41	---	Uncontrolled[e]	Higginbotham and Goldberg, 1981
154[f]	141-171	Mech. Ppt.	Zielke and Bittman, 1982

TABLE C-11. MEASURED BERYLLIUM EMISSION FACTORS FOR UTILITY PULVERIZED DRY BOTTOM BOILERS FIRED WITH BITUMINOUS COAL (Continued)

Emission Factor (lb/10^{12} Btu)			
Mean[a]	Range	Control Status	Reference
19.4[f]	18.1-22.1	Mech. Ppt/1st ESP in series of 2	Zielke and Bittman, 1982
0.082[g]	0.007-0.209	Mech. Ppt/2 ESPs in series	Zieklke and Bittman, 1982
---	0.97-1.7[h]	ESP	Ondov *et al*., 1979b
52[i]	44-59	Uncontrolled	Cowherd *et al*., 1975
33[i]	26-38	Mechanical Ppt.	Cowherd *et al*., 1975

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[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Average of tests of six different boilers.

[c] Average of eight tests of the same boiler.

[d] Boiler operating under baseline (design) conditions.

[e] Boiler operating under low-NO_x conditions - certain burners admit only air rather than fuel, or different fuel/air ratios are admitted than under design operating conditions.

[f] Average of seven tests of the same boiler.

[g] Average of five tests of the same boiler.

[h] Range for three tests of the same boiler.

[i] Average of three tests of the same boiler.

TABLE C-12. MEASURED BERYLLIUM EMISSION FACTORS FOR UTILITY PULVERIZED WET BOTTOM BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Control Status	Reference
0.88	Mechanical Ppt/ESP	Shih _et_ _al._, 1980b
1.7	ESP	Shih _et_ _al._, 1980b
1.0	ESP	Shih _et_ _al._, 1980b
0.086	Venturi Wet Scrubber	Shih _et_ _al._, 1980b
3.7	ESP	Shih _et_ _al._, 1980b
10.2	ESP	Shih _et_ _al._, 1980b

TABLE C-13. MEASURED BERYLLIUM EMISSION FACTORS FOR UTILITY CYCLONE BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Control Status	Reference
0.86	Wet Scrubber	Shih *et al.*, 1980b
0.60	ESP	Shih *et al.*, 1980b
1.05	ESP	Shih *et al.*, 1980b
0.19	ESP	Shih *et al.*, 1980b
0.23	ESP	Shih *et al.*, 1980b

TABLE C-14. MEASURED BERYLLIUM EMISSION FACTORS FOR UTILITY STOKER BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Control Status	Reference
0.13	Fabric Filter	Shih *et al.*, 1980b
5.6	Mechanical Ppt	Shih *et al.*, 1980b
20.0	Multiclone	Shih *et al.*, 1980b

TABLE C-15. MEASURED BERYLLIUM EMISSION FACTORS FOR UTILITY BOILERS FIRING SUBBITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Boiler Type	Control Status	Reference
18.0	Cyclone	Uncontrolled	Leavitt *et al.*, 1979
1.6	Cyclone	Venturi Scrubber	Leavitt *et al.*, 1979
0.60	Pulverized	Venturi Scrubber	Radian 1975
1.0	Pulverized	ESP (hot side)	Radian 1975
0.38	Unspecified	ESP (cold side)	Mann *et al.*, 1978
0.88	Unspecified	ESP (hot side)	Mann *et al.*, 1978

TABLE C-16. MEASURED BERYLLIUM EMISSION FACTORS FOR UTILITY BOILERS FIRING LIGNITE COAL

Emission Factor ($lb/10^{12}$ Btu)	Boiler Type	Control Status	Reference
2.3	Pulverized Dry Bottom	Multiclone	Shih *et al.*, 1980b
2.6	Pulverized Dry Bottom	Multiclone	Shih *et al.*, 1980b
<2.3	Pulverized Dry Bottom	ESP	Shih *et al.*, 1980b
0.70	Cyclone	ESP	Shih *et al.*, 1980b
6.8	Cyclone	Cyclone	Radian 1975
13.7	Spreader Stoker	Multiclone	Shih *et al.*, 1980b
0.26	Spreader Stoker	ESP	Shih *et al.*, 1980b

TABLE C-17. MEASURED BERYLLIUM EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Emission Factor ($lb/10^{12}$ Btu) Mean[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Boiler Type	Control Status	Reference
1.1[b]	---	Pulverized Dry Bottom	ESP	Baig et al., 1981
0.19	---	Pulverized Dry Bottom	ESP	Suprenant et al., 1980a
2.3	---	Pulverized Dry Bottom	Multiclone/Scrubber	Leavitt et al., 1978b; Fischer 1979
93	---	Pulverized Dry Bottom	Multiclone	Leavitt et al., 1978b; Fischer et al., 1979
15[c]	---	Pulverized Dry Bottom	Uncontrolled	McCurley et al., 1979
2[c]	---	Pulverized Dry Bottom	ESP	McCurley et al., 1979
0.21	---	Pulverized Wet Bottom	Multiclone	Suprenant et al., 1980a
4.0	---	Spreader Stoker	Multiclone/ESP	Suprenant et al., 1980a
3.3	---	Spreader Stoker	Multiclone	Suprenant et al., 1980a
12.1	---	Spreader Stoker	Multiclone	Suprenant et al., 1980a
1.8[c]	0.30-3.2	Spreader Stoker	Uncontrolled[d]	Burlingame et al., 1981
38.3[e]	11-72	Spreader Stoker	Uncontrolled[d]	Burlingame et al., 1981
65	---	Spreader Stoker	Uncontrolled[d]	Burlingame et al., 1981
6.5[c]	4.2-8.8	Spreader Stoker	Uncontrolled	Burlingame et al., 1981
15[c]	8.1-2.2	Spreader Stoker	Uncontrolled	Burlingame et al., 1981

TABLE C-17. MEASURED BERYLLIUM EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS (Continued)

Emission Factor ($lb/10^{12}$ Btu) Mean[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Boiler Type	Control Status	Reference
7.2[c]	6.7-7.6	Spreader Stoker	Uncontrolled	Burlingame *et al.*, 1981
7.0	---	Overfeed Stoker	Uncontrolled	Burlingame *et al.*, 1981
39	---	Overfeed Stoker	Uncontrolled	Burlingame *et al.*, 1981
16.5[c]	14-19	Overfeed Stoker	Uncontrolled	Burlingame *et al.*, 1981
3.9	---	Overfeed Stoker	Uncontrolled	Burlingame *et al.*, 1981
4.3[c]	3.7-4.9	Overfeed Stoker	Economizer, Dust Collector	Burlingame *et al.*, 1981
780	---	Spreader Stoker	Uncontrolled[f]	Lips and Higginbotham, 1981
120	---	Spreader Stoker	Mechanical Ppt/ESP[f]	Lips and Higginbotham, 1981
430	---	Spreader Stoker	Uncontrolled[g]	Lips and Higginbotham, 1981
0.20	---	Spreader Stoker	Mechanical Ppt/ESP[g]	Lips and Higginbotham, 1981

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[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Average of tests of three different boilers.

[c] Average of two tests of the same boiler.

[d] Traveling grate spreader stoker with re-injection from the dust collector. Measured upstream of control device.

[e] Average of three tests of the same boiler.

[f] Boiler operating under baseline (design) conditions.

[g] Boiler operating with low excess air level for NO_x control.

TABLE C-18. MEASURED BERYLLIUM EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Emission Factor ($lb/10^{12}$ Btu)				
Mean[a]	Range	Boiler Type	Control Status	Reference
51[b]	32-70	Spreader Stoker	Uncontrolled[c]	Burlingame *et al.*, 1981
57	---	Spreader Stoker	Uncontrolled[d]	Goldberg and Higgenbotham, 1981
3.3	---	Spreader Stoker	Mechanical Ppt/ESP[d]	Goldberg and Higgenbotham, 1981
6.2	---	Spreader Stoker	Uncontrolled[e]	Goldberg and Higgenbotham, 1981
0.77	---	Spreader Stoker	Mechanical Ppt/ESP[e]	Goldberg and Higgenbotham, 1981

---

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicated how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Mean of two tests of the same boiler.

[c] Traveling grate spreader stoker with re-injection from the dust collector. Measured upstream of controls.

[d] Tested while operating under baseline (design) conditions.

[e] Tested while operating under low-NO_x operating conditions - overfire air rate set at maximum level.

TABLE C-19. MEASURED BERYLLIUM EMISSION FACTORS FOR COMMERCIAL/INSTITUTIONAL COAL-FIRED BOILERS

Emission Factor ($lb/10^{12}$ Btu)	Coal Type	Boiler Type	Control Status	Reference
307.0	Bituminous	Pulverized Dry Bottom	Uncontrolled	Suprenant *et al.*, 1980b
0.95	Bituminous	Pulverized Dry Bottom	Multiclone/Scrubber	Suprenant *et al.*, 1980b
7.9	Bituminous	Spreader Stoker	Mechanical Ppt.	Suprenant *et al.*, 1980b
0.77	Bituminous	Overfeed Stoker	Mechanical Ppt.	Suprenant *et al.*, 1980b
21.8	Anthracite	Stoker	Uncontrolled	Suprenant *et al.*, 1980b
10.7	Anthracite	Stoker	Uncontrolled	Suprenant *et al.*, 1980b
0.93	Anthracite	Stoker	Uncontrolled	Suprenant *et al.*, 1980b

TABLE C-20. MEASURED CADMIUM EMISSION FACTORS FOR PULVERIZED DRY BOTTOM UTILITY BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)			
Mean[a]	Range	Control Status	Reference
2.6[b]	---	ESP	Baig et al., 1981
1.2	---	Wet Scrubber	Shih et al., 1980b
1.9	---	Mechanical Ppt/ESP	Shih et al., 1980b
1.4	---	Mechanical Ppt/ESP	Shih et al., 1980b
26.5[c]	11.4-52.8	ESP	Evers et al., 1980
137[c]	114-167	Uncontrolled	Evers et al., 1980
6.6	---	ESP[d]	Sawyer and Higginbotham, 1981a
9.8	---	ESP[e]	Sawyer and Higginbotham, 1981a
3.8	---	ESP[e]	Sawyer and Higginbotham, 1981a
41	---	Uncontrolled[d]	Sawyer and Higginbotham, 1981a
12	---	Uncontrolled[e]	Sawyer and Higginbotham, 1981a
11	---	Uncontrolled[e]	Sawyer and Higginbotham, 1981a
4.5	---	Low Effic. ESP[d]	Higginbotham and Goldberg, 1981
7.1	---	Low Effic. ESP[e]	Higginbotham and Goldberg, 1981
10	---	Uncontrolled[d]	Higginbotham and Goldberg, 1981
9.2	---	Uncontrolled[e]	Higginbotham and Goldberg, 1981
---	10-14	Uncontrolled	Scinto et al., 1981
<4.6	---	ESP	Scinto et al., 1981
<4.6	---	ESP/Scrubber	Scinto et al., 1981

TABLE C-20. MEASURED CADMIUM EMISSION FACTORS FOR PULVERIZED DRY BOTTOM UTILITY BOILERS FIRED WITH BITUMINOUS COAL (Continued)

Emission Factor ($lb/10^{12}$ Btu)			
Mean[a]	Range	Control Status	Reference
291[f]	136-487	Mechanical Ppt.	Zielke and Bittman, 1982
46	---	Mech. Ppt/2 ESPs in Series	Zielke and Bittman, 1982
1.95	---	Venturi Scrubber	Ondov *et al.*, 1979a; Hobbs *et al.*, 1983
---	0.22-0.6[g]	ESP	Ondov *et al.*, 1979b
31[h]	15-56	Mechanical Ppt.	Cowherd *et al.*, 1975
42[h]	24-74	Uncontrolled	Cowherd *et al.*, 1975

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[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single value was reported, it is included in this column.

[b] Average of tests of six boilers.

[c] Average of eight tests of the same boiler.

[d] Tested while boiler was operating under baseline (design) conditions.

[e] Tested while boiler was operating under low-NO_x conditions - certain burners admit air rather than fuel, or different fuel/air ratios are admitted than under design operating conditions.

[f] Average of seven tests of the same boiler.

[g] Range for four tests of the same boiler.

[h] Average of three tests of the same boiler.

TABLE C-21. MEASURED CADMIUM EMISSION FACTORS FOR UTILITY PULVERIZED WET BOTTOM BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Control Status	Reference
1.9	Mechanical Ppt/ESP	Shih *et al.*, 1980b
0.56	ESP	Shih *et al.*, 1980b
0.63	ESP	Shih *et al.*, 1980b
0.086	Venturi Scrubber	Shih *et al.*, 1980b
1.4	ESP	Shih *et al.*, 1980b
2.6	ESP	Shih *et al.*, 1980b

TABLE C-22. MEASURED CADMIUM EMISSION FACTORS FOR UTILITY CYCLONE BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)			
Mean[a]	Range	Control Status	Reference
488	---	Wet Scrubber	Shih *et al.*, 1980b
3.0	---	ESP	Shih *et al.*, 1980b
1.1	---	ESP	Shih *et al.*, 1980b
0.35	---	ESP	Shih *et al.*, 1980b
1.1	---	ESP	Shih *et al.*, 1980b
28.5[b]	22-35	Uncontrolled	Klein *et al.*, 1975b; Lyon, 1977
0.8[b]	0.7-0.9	ESP	Klein *et al.*, 1975b; Lyon, 1977

[a] This column gives the arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single value was reported, it is included in this column.

[b] Average of two tests of the same boiler.

TABLE C-23. MEASURED CADMIUM EMISSION FACTORS FOR UTILITY STOKER BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Control Status	Reference
0.33	Fabric Filter	Shih _et al._, 1980b
4.2	Mechanical Ppt.	Shih _et al._, 1980b
22.1	Multiclone	Shih _et al._, 1980b

TABLE C-24. MEASURED CADMIUM EMISSION FACTORS FOR UTILITY BOILERS FIRED WITH SUBBITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Boiler Type	Control Status	Reference
4400	Cyclone	Uncontrolled	Leavitt _et al._, 1979
490	Cyclone	Scrubber	Leavitt _et al._, 1979
4.0	Pulverized	Venturi Scrubber	Radian, 1975
<0.40	Pulverized	ESP (hot side)	Radian, 1975
0.39	NR	ESP (cold side)	Mann _et al._, 1978
1.7	NR	ESP (hot side)	Mann _et al._, 1978

NR - not reported.

TABLE C-25. MEASURED CADMIUM EMISSION FACTORS FOR UTILITY BOILERS FIRED WITH LIGNITE COAL

Emission Factor ($lb/10^{12}$ Btu)				
Mean[a]	Range	Boiler Type	Control Status	Reference
25.6	---	Pulverized Dry Bottom	Multiclone	Shih et al., 1980b
5.1	---	Pulverized Dry Bottom	Multiclone	Shih et al., 1980b
<3.5	---	Pulverized Dry Bottom	ESP	Shih et al., 1980b
1.2	---	Cyclone	ESP	Shih et al., 1980b
16	---	Cyclone	Cyclone	Radian, 1975
30.6[b]	1.8-59	Cyclone	ESP/Scrubbers	Schock et al., 1979
5.3	---	Spreader Stoker	Multiclone	Shih et al., 1980b
1.9	---	Spreader Stoker	ESP	Shih et al., 1980b

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only one value was reported, it is included in this column.

[b] Average of two tests of the same boiler.

TABLE C-26. MEASURED CADMIUM EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Emission Factor ($lb/10^{12}$ Btu) Mean[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Boiler Type	Control Status	Reference
20[b]	---	Pulverized Dry Bottom	ESP	Baig et al., 1981
0.49	---	Pulverized Dry Bottom	ESP	Suprenant et al., 1980a
465	---	Pulverized Dry Bottom	Multiclone	Leavitt et al., 1978b; Fischer et al., 1979
0.98	---	Pulverized Dry Bottom	Multiclone/Scrubber	Leavitt et al., 1978b; Fischer et al., 1979
290	---	Pulverized Dry Bottom	Uncontrolled	McCurley et al., 1979
39	---	Pulverized Dry Bottom	ESP	McCurley et al., 1979
1.5	---	Pulverized Wet Bottom	Multiclone	Suprenant et al., 1980a
0.009	---	Spreader Stoker	Multiclone/ESP	Suprenant et al., 1980a
0.19	---	Spreader Stoker	Multiclone	Suprenant et al., 1980a
0.93	---	Spreader Stoker	Multiclone	Suprenant et al., 1980a
4.8[c]	4.1-5.6	Spreader Stoker	Uncontrolled[d]	Burlingame et al., 1981
20[e]	16-23	Spreader Stoker	Uncontrolled[d]	Burlingame et al., 1981
35	---	Spreader Stoker	Uncontrolled[d]	Burlingame et al., 1981
8.7[c]	7.4-10	Spreader Stoker	Uncontrolled	Burlingame et al., 1981
22[c]	20-25	Spreader Stoker	Uncontrolled	Burlingame et al., 1981
45[c]	25-65	Spreader Stoker	Uncontrolled	Burlingame et al., 1981

TABLE C-26. MEASURED CADMIUM EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS (Continued)

Emission Factor ($lb/10^{12}$ Btu) Mean[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Boiler Type	Control Status	Reference
37	---	Overfeed Stoker	Uncontrolled	Burlingame et al., 1981
12	---	Overfeed Stoker	Uncontrolled	Burlingame et al., 1981
180[c]	60-300	Overfeed Stoker	Uncontrolled	Burlingame et al., 1981
100	---	Overfeed Stoker	Uncontrolled	Burlingame et al., 1981
56[c]	44-67	Overfeed Stoker	Economizer/Dust Collector	Burlingame et al., 1981
13	---	Spreader Stoker	Uncontrolled[f]	Lips and Higginbotham, 1981
1.3	---	Spreader Stoker	ESP[f]	Lips and Higginbotham, 1981
11	---	Spreader Stoker	Uncontrolled[g]	Lips and Higginbotham, 1981
4.2	---	Spreader Stoker	ESP[g]	Lips and Higginbotham, 1981

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Average of three boilers.

[c] Average of two tests of the same boilers.

[d] Traveling grate spreader stoker with re-injection from the dust collector. Measured upstream of control device.

[e] Average of three tests of the same boiler.

[f] Boiler operated under baseline (design) conditions.

[g] Boiler operated with low excess air level for NO_x control.

TABLE C-27. MEASURED CADMIUM EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Emission Factor ($lb/10^{12}$ Btu)				
Mean[a]	Range	Boiler Type	Control Status	Reference
14[b]	4.9-23	Spreader Stoker	Uncontrolled[c]	Burlingame *et al.*, 1981
78	---	Spreader Stoker	Uncontrolled[d]	Goldberg and Higginbotham, 1981
5.7	---	Spreader Stoker	Mechanical Ppt/ESP[d]	Goldberg and Higginbotham, 1981
290	---	Spreader Stoker	Uncontrolled[e]	Goldberg and Higginbotham, 1981
14	---	Spreader Stoker	Mechanical Ppt/ESP[e]	Goldberg and Higginbotham, 1981

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Mean of two tests of the same boiler.

[c] Traveling grate spreader stoker with re-injection from the dust collector. Measured upstream of controls.

[d] Tested while operating under baseline (design) conditions.

[e] Tested while operating under low-NO_x operating conditions - overfire air rate set at maximum level.

TABLE C-28. MEASURED CADMIUM EMISSION FACTORS FOR COMMERCIAL/INSTITUTIONAL COAL-FIRED BOILERS

Emission Factor ($lb/10^{12}$ Btu)	Type of Coal	Boiler Type	Control Status	Reference
12.8	Bituminous	Pulverized Dry Bottom	Uncontrolled	Suprenant *et al.*, 1980b
0.35	Bituminous	Pulverized Dry Bottom	Multiclone/Scrubber	Suprenant *et al.*, 1980b
5.6	Bituminous	Spreader Stoker	Mechanical Ppt.	Suprenant *et al.*, 1980b
1.2	Bituminous	Overfeed Stoker	Mechanical Ppt.	Suprenant *et al.*, 1980b
2.3	Anthracite	Stoker	Uncontrolled	Suprenant *et al.*, 1980b
3.5	Anthracite	Stoker	Uncontrolled	Suprenant *et al.*, 1980b
1.4	Anthracite	Stoker	Uncontrolled	Suprenant *et al.*, 1980b

TABLE C-29. MEASURED CADMIUM EMISSION FACTORS FOR COAL-FIRED RESIDENTIAL FURNACES

Emission Factor ($lb/10^{12}$ Btu)	Coal Type	Furnace Type	Control Status	Reference
155	Bituminous	NR[a]	Uncontrolled	DeAngelis and Reznik, 1979
31	Bituminous	NR	Uncontrolled	DeAngelis and Reznik, 1979
8.9[b]	Bituminous	Warm Air Furnace with Stoker	Uncontrolled	DeAngelis, 1979
<44.5[c]	Bituminous-washed	Warm Air Furnace with Stoker	Uncontrolled	DeAngelis, 1979

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[a] NR = not reported.

[b] Average of two tests of the same boiler.

[c] Average of two tests of the same boiler. Both were less than the detection limit of 44.5 $lb/10^{12}$ Btu.

TABLE C-30. MEASURED CHROMIUM EMISSION FACTORS FOR PULVERIZED DRY BOTTOM UTILITY BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor (lb/10^{12} Btu)			
Mean[a]	Range	Control Status	Reference
3000[b,c]	---	ESP	Baig *et al.*, 1981
12.3	---	Wet Scrubber	Shih *et al.*, 1980b
7970[b]	---	Mechanical Ppt/ESP	Shih *et al.*, 1980b
3930[b]	---	Mechanical Ppt/ESP	Shih *et al.*, 1980b
7900	---	Uncontrolled[d]	Sawyer and Higginbotham, 1981a
3700	---	ESP[d]	Sawyer and Higginbotham, 1981a
2300	---	Uncontrolled[e]	Sawyer and Higginbotham, 1981a
380	---	Uncontrolled[e]	Sawyer and Higginbotham, 1981a
2400	---	Uncontrolled[d]	Higginbotham and Goldberg, 1981
2800	---	Uncontrolled[e]	Higginbotham and Goldberg, 1981
2000	---	Uncontrolled[e]	Higginbotham and Goldberg, 1981
2500	---	Uncontrolled[e]	Higginbotham and Goldberg, 1981
390	---	ESP[e]	Higginbotham and Goldberg, 1981
1000	---	ESP[e]	Higginbotham and Goldberg, 1981
244	---	Uncontrolled	Scinto *et al.*, 1981
17.3	---	ESP/Scrubber	Scinto *et al.*, 1981
17,200[f]	8200-29,700	Mechanical Ppt.	Zielke and Bittman, 1982
3780[g]	1520-7210	Mech. Ppt/1st ESP in Series of 2	Zielke and Bittman, 1982
740[h]	<74-1740	Mech. Ppt/2 ESPs in Series	Zielke and Bittman, 1982

TABLE C-30. MEASURED CHROMIUM EMISSION FACTORS FOR PULVERIZED DRY BOTTOM UTILITY BOILERS FIRED WITH BITUMINOUS COAL (Continued)

Emission Factor ($lb/10^{12}$ Btu) Mean[a]	Range	Control Status	Reference
48	---	Venturi Scrubber	Ondov _et al._, 1979a
31	4.5-290	Venturi Scrubber	Ondov _et al._, 1979a
12	---	Venturi Scrubber	Ondov _et al._, 1979a
1.9[i]	1.6-2.3	ESP	Ondov _et al._, 1979b
---	7.1-70.8[j]	ESP	Ondov _et al._, 1979b
770	510-1120	Mech. Collector	Cowherd _et al._, 1975
1320[i]	1000-1840	Uncontrolled	Cowherd _et al._, 1975
0.0034[k]	---	Controlled	Ajax and Cuffe, 1985

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[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single value was reported, it is included in this column.

[b] Suspected corrosion of sampling train components may account for higher than expected measured values.

[c] Average of tests of six boilers.

[d] Tested while boiler was operating under baseline (design) conditions.

[e] Tested while boiler was operating under low-NO_x conditions - certain burners admit air rather than fuel, or different fuel/air ratios are admitted than under design operating conditions.

[f] Average of seven tests of the same boiler.

[g] Average of six tests of the same boiler.

[h] Average of four tests of the same boiler.

[i] Average of three tests of the same boiler.

[j] Range for six tests of the same boiler.

[k] Average reported for three tests of the same boiler. This value is for hexavalent chromium (Cr+6).

TABLE C-31. MEASURED CHROMIUM EMISSION FACTORS FOR UTILITY PULVERIZED WET BOTTOM BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor[a] ($lb/10^{12}$ Btu)	Control Status	Reference
86	Mechanical Ppt/ESP	Shih *et al.*, 1980b
339	ESP	Shih *et al.*, 1980b
2040	ESP	Shih *et al.*, 1980b
0.60	Venturi Scrubber	Shih *et al.*, 1980b
3320	ESP	Shih *et al.*, 1980b
3070	ESP	Shih *et al.*, 1980b

[a] The reference notes that suspected corrosion of the sampling train may account for higher than expected values.

TABLE C-32. MEASURED CHROMIUM EMISSION FACTORS FOR UTILITY CYCLONE BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu) Mean[a]	Range	Control Status	Reference
107	---	Wet Scrubber	Shih *et al.*, 1980b
1820	---	ESP	Shih *et al.*, 1980b
5340[b]	---	ESP	Shih *et al.*, 1980b
674[b]	---	ESP	Shih *et al.*, 1980b
1170[b]	---	ESP	Shih *et al.*, 1980b
1150[c]	1000-1300	Uncontrolled	Klein *et al.*, 1975b; Lyon, 1977
32[c]	18-46	ESP	Klein *et al.*, 1975b; Lyon, 1977

[a] This column gives the arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single value was reported, it is included in this column.

[b] Reference notes that suspected corrosion of sampling train may account for higher than expected values.

[c] Average of two tests of the same boiler.

TABLE C-33. MEASURED CHROMIUM EMISSION FACTORS FOR UTILITY STOKER BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor[a] (lb/10^{12} Btu)	Control Status	Reference
153	Fabric Filter	Shih *et al.*, 1980b
2420	Mechanical Ppt.	Shih *et al.*, 1980b
455	Multiclone	Shih *et al.*, 1980b

[a] Reference notes that suspected corrosion of the sampling train may account for higher values than expected.

TABLE C-34. MEASURED CHROMIUM EMISSION FACTORS FOR UTILITY BOILERS FIRED WITH SUBBITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Boiler Type	Control Status	Reference
1100	Cyclone	Uncontrolled	Leavitt *et al.*, 1979
100	Cyclone	Scrubber	Leavitt *et al.*, 1979
390	Pulverized	Venturi Scrubber	Radian, 1975
140	Pulverized	ESP	Radian, 1975
8.8	NR	ESP	Mann *et al.*, 1978
28	NR	ESP	Mann *et al.*, 1978

NR - Not Reported.

TABLE C-35. MEASURED CHROMIUM EMISSION FACTORS FOR UTILITY BOILERS FIRED WITH LIGNITE COAL

Mean[a]	Range	Boiler Type	Control Status	Reference
74.4	---	Pulverized Dry Bottom	Multiclone	Shih *et al.*, 1980b
67.4	---	Pulverized Dry Bottom	Multiclone	Shih *et al.*, 1980b
20.0	---	Pulverized Dry Bottom	ESP	Shih *et al.*, 1980b
<7.7	---	Cyclone	ESP	Shih *et al.*, 1980b
1000	---	Cyclone	Cyclone	Radian, 1975
4.6[b]	3.1-5.9	Cyclone	ESP/Scrubbers	Schock *et al.*, 1979
30.2	---	Spreader Stoker	Multiclone	Shih *et al.*, 1980b
<5.3	---	Spreader Stoker	ESP	Shih *et al.*, 1980b

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only one value was reported, it is included in this column.

[b] Average of two tests of the same boiler.

TABLE C-36. MEASURED CHROMIUM EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Emission Factor (lb/10^{12} Btu)				
Mean[a]	Range	Boiler Type	Control Status	Reference
1500[b,c]	---	Pulverized Dry Bottom	ESP	Baig et al., 1980
5.8	---	Pulverized Dry Bottom	ESP	Suprenant et al., 1980a
2560	---	Pulverized Dry Bottom	Multiclone	Leavitt et al., 1978b; Fischer et al., 1979
126	---	Pulverized Dry Bottom	Multiclone/Scrubber	Leavitt et al., 1978b; Fischer et al., 1979
12.3	---	Pulverized Wet Bottom	Multiclone	Suprenant et al., 1980a
17.2	---	Spreader Stoker	Multiclone/ESP	Suprenant et al., 1980a
325	---	Spreader Stoker	Multiclone	Suprenant et al., 1980a
62	---	Spreader Stoker	Multiclone	Suprenant et al., 1980a
58[d]	15-100	Spreader Stoker	Uncontrolled[e]	Burlingame et al., 1981
4800[f]	3500-7200	Spreader Stoker	Uncontrolled[e]	Burlingame et al., 1981
6500	---	Spreader Stoker	Uncontrolled[e]	Burlingame et al., 1981
3200[d]	390-6000	Spreader Stoker	Uncontrolled	Burlingame et al., 1981
5150[d]	2600-7700	Spreader Stoker	Uncontrolled	Burlingame et al., 1981
7450[d]	6500-8400	Spreader Stoker	Uncontrolled	Burlingame et al., 1981

TABLE C-36. MEASURED CHROMIUM EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS (Continued)

Emission Factor (lb/10^{12} Btu) Mean[a]	Emission Factor (lb/10^{12} Btu) Range	Boiler Type	Control Status	Reference
2300	---	Overfeed Stoker	Uncontrolled	Burlingame et al., 1981
1400	---	Overfeed Stoker	Uncontrolled	Burlingame et al., 1981
31,500[d]	14,000-49,000	Overfeed Stoker	Uncontrolled	Burlingame et al., 1981
2300	---	Overfeed Stoker	Uncontrolled	Burlingame et al., 1981
15,400[d]	8,800-22,000	Overfeed Stoker	Economizer/Dust Collector	Burlingame et al., 1981
30	---	Spreader Stoker	Uncontrolled[g]	Lips and Higginbotham, 1981
16	---	Spreader Stoker	Mechanical Ppt/ESP[g]	Lips and Higginbotham, 1981
1.5[h]	---	Spreader Stoker	2 Mechanical Ppt in Series	Ajax and Cuffe, 1985

---

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Suspected corrosion of the sampling train components may account for higher than expected values.

[c] Average for three boilers.

[d] Average of two tests of the same boiler.

[e] Traveling grate spreader stoker with re-injection from the dust collector. Measured upstream of control device.

[f] Average of three tests of the same boiler.

[g] Boiler operated with low excess air level for NO_x control.

[h] Average of three tests of the same boiler. This value is for hexavalent chromium (Cr+6).

TABLE C-37. MEASURED CHROMIUM EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Emission Factor ($lb/10^{12}$ Btu) Mean[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Boiler Type	Control Status	Reference
3050[b]	2600-3500	Spreader Stoker	Uncontrolled[c]	Burlingame *et al.*, 1981
640	---	Spreader Stoker	Uncontrolled[d]	Goldberg and Higginbotham, 1981
15	---	Spreader Stoker	Mechanical Ppt/ESP[d]	Goldberg and Higginbotham, 1981
280	---	Spreader Stoker	Uncontrolled[e]	Goldberg and Higginbotham, 1981
120	---	Spreader Stoker	Mechanical Ppt/ESP[e]	Goldberg and Higginbotham, 1981

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Mean of two tests of the same boiler.

[c] Traveling grate spreader stoker with re-injection from the dust collector. Measured upstream of controls.

[d] Tested while operating under baseline (design) conditions.

[e] Tested while operating under low-NO_x operating conditions - overfire air rate set at maximum level.

TABLE C-38. MEASURED CHROMIUM EMISSION FACTORS FOR COMMERCIAL/INSTITUTIONAL COAL-FIRED BOILERS

Emission Factor ($lb/10^{12}$ Btu)	Type of Coal	Boiler Type	Control Status	Reference
1920	Bituminous	Pulverized Dry Bottom	Uncontrolled	Suprenant et al., 1980b
18.1	Bituminous	Pulverized Dry Bottom	Multiclone/Scrubber	Suprenant et al., 1980b
18.8	Bituminous	Underfeed Stoker	Uncontrolled	Suprenant et al., 1980b
100	Bituminous	Spreader Stoker	Mechanical Ppt.	Suprenant et al., 1980b
1840	Bituminous	Overfeed Stoker	Mechanical Ppt.	Suprenant et al., 1980b
240	Anthracite	Stoker	Uncontrolled	Suprenant et al., 1980b
1510	Anthracite	Stoker	Uncontrolled	Suprenant et al., 1980b
876	Anthracite	Stoker	Uncontrolled	Suprenant et al., 1980b

TABLE C-39. MEASURED CHROMIUM EMISSION FACTORS FOR COAL-FIRED RESIDENTIAL FURNACES

Emission Factor ($lb/10^{12}$ Btu)	Coal Type	Furnace Type	Control Status	Reference
387	Bituminous	NR[a]	Uncontrolled	DeAngelis and Reznik, 1979
155	Bituminous	NR	Uncontrolled	DeAngelis and Reznik, 1979
44.5[b]	Bituminous	Warm Air Furnace with Stoker	Uncontrolled	DeAngelis, 1979
267[b]	Bituminous-washed	Warm Air Furnace with Stoker	Uncontrolled	DeAngelis, 1979

[a] NR = Not Reported.

[b] Average of two tests of the same boiler.

TABLE C-40. MEASURED COPPER EMISSION FACTORS FOR PULVERIZED DRY BOTTOM UTILITY BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu) Mean[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Control Status	Reference
13.5	---	Wet Scrubber	Shih et al., 1980b
177	---	Mechanical Ppt/ESP	Shih et al., 1980b
48.8	---	Mechanical Ppt/ESP	Shih et al., 1980b
268[b]	92.4-660	ESP	Evers et al., 1980
896[b]	792-1010	Uncontrolled	Evers et al., 1980
1000	---	Uncontrolled[c]	Sawyer and Higginbotham, 1981a
680	---	Uncontrolled[d]	Sawyer and Higginbotham, 1981a
780	---	Uncontrolled[d]	Sawyer and Higginbotham, 1981a
100	---	ESP[c]	Sawyer and Higginbotham, 1981a
48	---	ESP[d]	Sawyer and Higginbotham, 1981a
82	---	ESP[d]	Sawyer and Higginbotham, 1981a
1100	---	Uncontrolled[c]	Higginbotham and Goldberg, 1981
830	---	Uncontrolled[d]	Higginbotham and Goldberg, 1981
490	---	Uncontrolled[d]	Higginbotham and Goldberg, 1981
1500	---	Uncontrolled[d]	Higginbotham and Goldberg, 1981
240	---	ESP[c]	Higginbotham and Goldberg, 1981
290	---	ESP[d]	Higginbotham and Goldberg, 1981
220	---	ESP[d]	Higginbotham and Goldberg, 1981
541	---	Uncontrolled	Scinto et al., 1981
34	---	ESP	Scinto et al., 1981

TABLE C-40. MEASURED COPPER EMISSION FACTORS FOR PULVERIZED DRY BOTTOM UTILITY BOILERS FIRED WITH BITUMINOUS COAL (Continued)

Emission Factor ($lb/10^{12}$ Btu)			
Mean[a]	Range	Control Status	Reference
14.1	---	ESP/Scrubber	Scinto _et al._, 1981
2720[e]	2380-3140	Mechanical Ppt.	Zielke and Bittman, 1982
580[e]	440-974	Mech. Ppt/1st ESP in Series of 2	Zielke and Bittman, 1982
34.5[f]	1.6-71.0	Mech. Ppt/2 ESPs in Series	Zielke and Bittman, 1982
27	10.1-54	Venturi Scrubber	Ondov _et al._, 1979a
20	---	Venturi Scrubber	Ondov _et al._, 1979a
440[g]	380-480	Uncontrolled	Cowherd _et al._, 1975
260[g]	210-290	Mechanical Ppt.	Cowherd _et al._, 1975

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single value was reported, it is included in this column.

[b] Average of eight tests of the same boiler.

[c] Tested while boiler was operating under baseline (design) conditions.

[d] Tested while boiler was operating under low-NO_x conditions - certain burners admit air rather than fuel, or different fuel/air ratios are admitted than under design operating conditions.

[e] Average of seven tests of the same boiler.

[f] Average of five tests of the same boiler.

[g] Average of three tests of the same boiler.

TABLE C-41. MEASURED COPPER EMISSION FACTORS FOR UTILITY PULVERIZED WET BOTTOM BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Control Status	Reference
23.2	Mechanical Ppt/ESP	Shih *et al.*, 1980b
12.3	ESP	Shih *et al.*, 1980b
30.2	ESP	Shih *et al.*, 1980b
2.3	Venturi Scrubber	Shih *et al.*, 1980b
137	ESP	Shih *et al.*, 1980b
225	ESP	Shih *et al.*, 1980b

TABLE C-42. MEASURED COPPER EMISSION FACTORS FOR UTILITY CYCLONE BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)			
Mean[a]	Range	Control Status	Reference
167	---	Wet Scrubber	Shih et al., 1980b
19.5	---	ESP	Shih et al., 1980b
22.8	---	ESP	Shih et al., 1980b
44.2	---	ESP	Shih et al., 1980b
23.2	---	ESP	Shih et al., 1980b
10.8[b]	7.0-14.5	Uncontrolled	Klein et al., 1975b; Lyon, 1977
0.26[b]	0.05-0.48	ESP	Klein et al., 1975b; Lyon, 1977

[a] This column gives the arithmetic values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single value was reported, it is included in this column.

[b] Average of two tests of the same boiler.

TABLE C-43. MEASURED COPPER EMISSION FACTORS FOR UTILITY STOKER BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Control Status	Reference
5.8	Fabric Filter	Shih *et al.*, 1980b
342	Mechanical Ppt.	Shih *et al.*, 1980b
188	Multiclone	Shih *et al.*, 1980b

TABLE C-44. MEASURED COPPER EMISSION FACTORS FOR UTILITY BOILERS FIRED WITH SUBBITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Boiler Type	Control Status	Reference
1000	Cyclone	Uncontrolled	Leavitt *et al.*, 1979
170	Cyclone	Scrubber	Leavitt *et al.*, 1979
29	Pulverized	Venturi Scrubber	Radian, 1975
30	Pulverized	ESP	Radian, 1975
82	NR	ESP	Mann *et al.*, 1978
50	NR	ESP	Mann *et al.*, 1978

NR - Not Reported.

TABLE C-45. MEASURED COPPER EMISSION FACTORS FOR UTILITY BOILERS FIRED WITH LIGNITE COAL

Emission Factor ($lb/10^{12}$ Btu)	Boiler Type	Control Status	Reference
376	Pulverized Dry Bottom	Multiclone	Shih _et_ _al._, 1980b
195	Pulverized Dry Bottom	Multiclone	Shih _et_ _al._, 1980b
<69.7	Pulverized Dry Bottom	ESP	Shih _et_ _al._, 1980b
30.2	Cyclone	ESP	Shih _et_ _al._, 1980b
480	Cyclone	Cyclone	Radian, 1975
193	Spreader Stoker	Multiclone	Shih _et_ _al._, 1980b
46.5	Spreader Stoker	ESP	Shih _et_ _al._, 1980b

TABLE C-46. MEASURED COPPER EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Emission Factor ($lb/10^{12}$ Btu) Mean[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Boiler Type	Control Status	Reference
80.6	---	Pulverized Dry Bottom	ESP	Suprenant et al., 1980a
19.5	---	Pulverized Dry Bottom	Multiclone/Scrubber	Leavitt, 1978b; Fischer, 1979
9530	---	Pulverized Dry Bottom	Multiclone	Leavitt, 1978b; Fischer, 1979
3150	---	Pulverized Dry Bottom	Uncontrolled	McCurley et al., 1979
230	---	Pulverized Dry Bottom	ESP	McCurley et al., 1979
45.1	---	Pulverized Wet Bottom	Multiclone	Suprenant et al., 1980a
309	---	Spreader Stoker	Multiclone/ESP	Suprenant et al., 1980a
411	---	Spreader Stoker	Multiclone	Suprenant et al., 1980a
1170	---	Spreader Stoker	Multiclone	Suprenant et al., 1980a
32[b]	17-46	Spreader Stoker	Uncontrolled[c]	Burlingame et al., 1981
1100[d]	1100-1100	Spreader Stoker	Uncontrolled[c]	Burlingame et al., 1981
600	---	Spreader Stoker	Uncontrolled[c]	Burlingame et al., 1981
192[b]	63-320	Spreader Stoker	Uncontrolled	Burlingame et al., 1981
180[b]	130-230	Spreader Stoker	Uncontrolled	Burlingame et al., 1981
880[b]	760-1000	Spreader Stoker	Uncontrolled	Burlingame et al., 1981
3500	---	Overfeed Stoker	Uncontrolled	Burlingame et al., 1981

TABLE C-46. MEASURED COPPER EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS (Continued)

Emission Factor ($lb/10^{12}$ Btu)				
Mean[a]	Range	Boiler Type	Control Status	Reference
720	---	Overfeed Stoker	Uncontrolled	Burlingame _et_ _al._, 1981
3300[b]	1300-5300	Overfeed Stoker	Uncontrolled	Burlingame _et_ _al._, 1981
200	---	Overfeed Stoker	Uncontrolled	Burlingame _et_ _al._, 1981
4550[b]	4200-4900	Overfeed Stoker	Economizer/Dust Collector	Burlingame _et_ _al._, 1981
300	---	Spreader Stoker	Uncontrolled[e]	Lips and Higginbotham, 1981
66	---	Spreader Stoker	Mechanical Ppt/ESP[e]	Lips and Higginbotham, 1981
5.2	---	Spreader Stoker	Uncontrolled[f]	Lips and Higginbotham, 1981
0.040	---	Spreader Stoker	Mechanical Ppt/ESP[f]	Lips and Higginbotham, 1981

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Average of two tests of the same boiler.

[c] Traveling grate spreader stoker with re-injection from the dust collector. Measured upstream of control device.

[d] Average of three tests of the same boiler.

[e] Boiler operated under baseline (design) conditions.

[f] Boiler operated with low excess air level for NO_x control.

TABLE C-47. MEASURED COPPER EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Emission Factor ($lb/10^{12}$ Btu)				
Mean[a]	Range	Boiler Type	Control Status	Reference
2900[b]	2800-3000	Spreader Stoker	Uncontrolled[c]	Burlingame *et al.*, 1981
2200	---	Spreader Stoker	Uncontrolled[d]	Goldberg and Higginbotham, 1981
18	---	Spreader Stoker	Mechanical Ppt/ESP[d]	Goldberg and Higginbotham, 1981
280	---	Spreader Stoker	Uncontrolled[e]	Goldberg and Higginbotham, 1981
74	---	Spreader Stoker	Mechanical Ppt/ESP[e]	Goldberg and Higginbotham, 1981

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[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Mean of two tests of the same boiler.

[c] Traveling grate spreader stoker with re-injection from the dust collector. Measured upstream of controls.

[d] Tested while operating under baseline (design) conditions.

[e] Tested while operating under low-NO_x operating conditions - overfire air rate set at maximum level.

TABLE C-48. MEASURED COPPER EMISSION FACTORS FOR COAL-FIRED RESIDENTIAL FURNACES

Emission Factor (lb/10^{12} Btu)	Coal Type	Furnace Type	Control Status	Reference
38.7	Bituminous	NR[a]	Uncontrolled	DeAngelis and Reznik, 1979
232	Bituminous	NR	Uncontrolled	DeAngelis and Reznik, 1979
356[b]	Bituminous	Warm Air Furnace with Stoker	Uncontrolled	DeAngelis, 1979
178[b]	Bituminous-washed	Warm Air Furnace with Stoker	Uncontrolled	DeAngelis, 1979

[a] NR = not reported.

[b] Average of two tests of the same boiler.

TABLE C-49. MEASURED COPPER EMISSION FACTORS FOR COMMERCIAL/INSTITUTIONAL COAL-FIRED BOILERS

Emission Factor ($lb/10^{12}$ Btu)	Type of Coal	Boiler Type	Control Status	Reference
1410	Bituminous	Pulverized Dry Bottom	Uncontrolled	Suprenant et al., 1980b
28	Bituminous	Pulverized Dry Bottom	Multiclone/Scrubber	Suprenant et al., 1980b
5.1	Bituminous	Underfeed Stoker	Uncontrolled	Suprenant et al., 1980b
184	Bituminous	Spreader Stoker	Mechanical Ppt.	Suprenant et al., 1980b
153	Bituminous	Overfeed Stoker	Mechanical Ppt.	Suprenant et al., 1980b
265	Anthracite	Stoker	Uncontrolled	Suprenant et al., 1980b
723	Anthracite	Stoker	Uncontrolled	Suprenant et al., 1980b
232	Anthracite	Stoker	Uncontrolled	Suprenant et al., 1980b

TABLE C-50. MEASURED MERCURY EMISSION FACTORS FOR PULVERIZED DRY BOTTOM UTILITY BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)			
Mean[a]	Range	Control Status	Reference
11[b]	---	ESP	Baig *et al.*, 1981
ND[c]	---	Wet Scrubber	Shih *et al.*, 1980b
22.1	---	Mechanical Ppt/ESP	Shih *et al.*, 1980b
22.3	---	Mechanical Ppt/ESP	Shih *et al.*, 1980b
5.9[d]	3.6-8.2	Mechanical Ppt/ESP	Kalb, 1975
5.8[e]	1.32-9.68	ESP	Evers *et al.*, 1980
72[e]	11.4-308	Uncontrolled	Evers *et al.*, 1980
23	---	Uncontrolled[f]	Sawyer and Higginbotham, 1981a
18	---	ESP[f]	Sawyer and Higginbotham, 1981a
10	---	Uncontrolled[g]	Higginbotham and Goldberg, 1981
3.9	---	Uncontrolled[f]	Higginbotham and Goldberg, 1981
16	---	Uncontrolled[f]	Higginbotham and Goldberg, 1981
1.5	---	ESP[g]	Higginbotham and Goldberg, 1981
2.6	---	ESP[f]	Higginbotham and Goldberg, 1981
2.0	---	ESP[f]	Higginbotham and Goldberg, 1981
3.1	---	ESP[f]	Higginbotham and Goldberg, 1981
8.5[h]	3.7-21.2	Mechanical Ppt.	Zielke and Bittman, 1982

TABLE C-50. MEASURED MERCURY EMISSION FACTORS FOR PULVERIZED DRY BOTTOM UTILITY BOILERS FIRED WITH BITUMINOUS COAL (Continued)

Emission Factor ($lb/10^{12}$ Btu) Mean[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Control Status	Reference
0.75[h]	0.41-2.0	Mech. Ppt/1st ESP in Series of 2	Zielke and Bittman, 1982
0.20[i]	<0.011-0.561	Mech. Ppt/2 ESPs in Series	Zielke and Bittman, 1982

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single value was reported, it is included in this column.

[b] Average of tests of six boilers.

[c] ND = not detected.

[d] Average of 14 tests of the same boiler.

[e] Average of eight tests of the same boiler.

[f] Tested while boiler was operating under low-NO_x conditions - certain burners admit air rather than fuel, or different fuel/air ratios are admitted than under design operating conditions.

[g] Tested while boiler was operating under baseline (design) conditions.

[h] Average of seven tests of the same boiler.

[i] Average of five tests of the same boiler.

TABLE C-51. MEASURED MERCURY EMISSION FACTORS FOR UTILITY PULVERIZED WET BOTTOM BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Control Status	Reference
5.3	Mechanical Ppt/ESP	Shih _et al._, 1980b
2.6	ESP	Shih _et al._, 1980b
4.2	ESP	Shih _et al._, 1980b
0.16	Venturi Scrubber	Shih _et al._, 1980b
5.1	ESP	Shih _et al._, 1980b
6.3	ESP	Shih _et al._, 1980b

TABLE C-52. MEASURED MERCURY EMISSION FACTORS FOR UTILITY CYCLONE BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Control Status	Reference
4.9	Wet Scrubber	Shih _et al._, 1980b
3.95	ESP	Shih _et al._, 1980b
5.1	ESP	Shih _et al._, 1980b
9.5	ESP	Shih _et al._, 1980b
17.7	ESP	Shih _et al._, 1980b
10	Uncontrolled	Klein _et al._, 1975b; Lyon, 1977
6.1	ESP	Klein _et al._, 1975b; Lyon, 1977

TABLE C-53. MEASURED MERCURY EMISSION FACTORS FOR UTILITY STOKER BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Control Status	Reference
4.6	Fabric Filter	Shih *et al.*, 1980b
26	Mechanical Ppt.	Shih *et al.*, 1980b
2.5	Multiclone	Shih *et al.*, 1980b

TABLE C-54. MEASURED MERCURY EMISSION FACTORS FOR UTILITY BOILERS FIRED WITH SUBBITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Boiler Type	Control Status	Reference
81	Cyclone	Uncontrolled	Leavitt *et al.*, 1979
4.9	Cyclone	Scrubber	Leavitt *et al.*, 1979
11	Pulverized	Venturi Scrubber	Radian, 1975
4.1	Pulverized	ESP	Radian, 1975
2.0	NR[a]	ESP	Mann, 1978
1.7	NR	ESP	Mann, 1978

[a] NR = not reported.

TABLE C-55. MEASURED MERCURY EMISSION FACTORS FOR UTILITY BOILERS FIRED WITH LIGNITE COAL

Emission Factor ($lb/10^{12}$ Btu)	Boiler Type	Control Status	Reference
4.4	Pulverized Dry Bottom	Multiclone	Shih *et al.*, 1980b
6.5	Pulverized Dry Bottom	Multiclone	Shih *et al.*, 1980b
<0.23	Pulverized Dry Bottom	ESP	Shih *et al.*, 1980b
0.46	Cyclone	ESP	Shih *et al.*, 1980b
22	Cyclone	Cyclone	Radian, 1975
5.6	Spreader Stoker	Multiclone	Shih *et al.*, 1980b
0.53	Spreader Stoker	ESP	Shih *et al.*, 1980b

TABLE C-56. MEASURED MERCURY EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Emission Factor ($lb/10^{12}$ Btu) Mean^a	Range	Boiler Type	Control Status	Reference
4.2^b	---	Pulverized Dry Bottom	ESP	Baig et al., 1981
4.4	---	Pulverized Dry Bottom	ESP	Suprenant et al., 1980a
180	---	Pulverized Dry Bottom	Multiclone	Leavitt et al., 1978b; Fischer et al., 1979
86	---	Pulverized Dry Bottom	Multiclone/Scrubber	Leavitt et al., 1978b; Fischer et al., 1979
6,7	---	Pulverized Wet Bottom	Multiclone	Suprenant et al., 1980a
4.2	---	Spreader Stoker	Multiclone/ESP	Suprenant et al., 1980a
5.8	---	Spreader Stoker	Multiclone	Suprenant et al., 1980a
25.1	---	Spreader Stoker	Multiclone	Suprenant et al., 1980a
0.77^c	0.76-0.78	Spreader Stoker	Uncontrolled^d	Burlingame et al., 1981
3.9^e	2.5-5.1	Spreader Stoker	Uncontrolled^d	Burlingame et al., 1981
2.3	---	Spreader Stoker	Uncontrolled^d	Burlingame et al., 1981
1.6^c	1.3-2.0	Spreader Stoker	Uncontrolled	Burlingame et al., 1981
3.2^c	2.5-3.9	Spreader Stoker	Uncontrolled	Burlingame et al., 1981
4.0^c	1.6-6.5	Spreader Stoker	Uncontrolled	Burlingame et al., 1981

TABLE C-56. MEASURED MERCURY EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS (Continued)

Emission Factor ($lb/10^{12}$ Btu)				
Mean[a]	Range	Boiler Type	Control Status	Reference
0.011	---	Overfeed Stoker	Uncontrolled	Burlingame et al., 1981
1.7	---	Overfeed Stoker	Uncontrolled	Burlingame et al., 1981
1.3[c]	0.74-1.9	Overfeed Stoker	Uncontrolled	Burlingame et al., 1981
2.1	---	Overfeed Stoker	Uncontrolled	Burlingame et al., 1981
0.80[c]	0.39-1.2	Overfeed Stoker	Economizer/Dust Collector	Burlingame et al., 1981
4.1	---	Spreader Stoker	Uncontrolled[f]	Lips and Higginbotham, 1981
2.4	---	Spreader Stoker	Mechanical Ppt/ESP[f]	Lips and Higginbotham, 1981
12	---	Spreader Stoker	Uncontrolled[g]	Lips and Higginbotham, 1981
1.0	---	Spreader Stoker	Mechanical Ppt/ESP[g]	Lips and Higginbotham, 1981

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Average for three boilers.

[c] Average of two tests of the same boiler.

[d] Traveling grate spreader stoker with re-injection from the dust collector. Measured upstream of control device.

[e] Average of three tests of the same boiler.

[f] Boiler operated under baseline (design) conditions.

[g] Boiler operated with low excess air level for NO_x control.

TABLE C-57. MEASURED MERCURY EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Emission Factor (lb/10^{12} Btu)				
Mean[a]	Range	Boiler Type	Control Status	Reference
8.9[b]	0.86-17	Spreader Stoker	Uncontrolled[c]	Burlingame *et al.*, 1981
0.64	---	Spreader Stoker	Uncontrolled[d]	Goldberg and Higginbotham, 1981
0.64	---	Spreader Stoker	Mechanical Ppt/ESP[d]	Goldberg and Higginbotham, 1981
0.91	---	Spreader Stoker	Uncontrolled[e]	Goldberg and Higginbotham, 1981
0.37	---	Spreader Stoker	Mechanical Ppt/ESP[e]	Goldberg and Higginbotham, 1981

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Mean of two tests of the same boiler.

[c] Traveling grate spreader stoker with re-injection from the dust collector. Measured upstream of controls.

[d] Tested while operating under baseline (design) conditions.

[e] Tested while operating under low-NO_x conditions - overfire air rate set at maximum level.

TABLE C-58. MEASURED MERCURY EMISSION FACTORS FOR COMMERCIAL/INSTITUTIONAL COAL-FIRED BOILERS

Emission Factor ($lb/10^{12}$ Btu)	Type of Coal	Boiler Type	Control Status	Reference
5.8	Bituminous	Pulverized Dry Bottom	Uncontrolled	Suprenant *et al.*, 1980b
1.1	Bituminous	Pulverized Dry Bottom	Multiclone/Scrubber	Suprenant *et al.*, 1980b
0.42	Bituminous	Underfeed Stoker	Uncontrolled	Suprenant *et al.*, 1980b
1.4	Bituminous	Spreader Stoker	Mechanical Ppt.	Suprenant *et al.*, 1980b
13.0	Bituminous	Overfeed Stoker	Mechanical Ppt.	Suprenant *et al.*, 1980b
7.0	Anthracite	Stoker	Uncontrolled	Suprenant *et al.*, 1980b
3.5	Anthracite	Stoker	Uncontrolled	Suprenant *et al.*, 1980b
5.3	Anthracite	Stoker	Uncontrolled	Suprenant *et al.*, 1980b

TABLE C-59. MEASURED MERCURY EMISSION FACTORS FOR COAL-FIRED RESIDENTIAL FURNACES

Emission Factor (lb/10^{12} Btu)	Coal Type	Furnace Type	Control Status	Reference
7.7	Bituminous Coal	NR[a]	Uncontrolled	DeAngelis and Reznik, 1979
23.2	Bituminous Coal	NR	Uncontrolled	DeAngelis and Reznik, 1979
26.7[b]	Bituminous Coal	Warm Air Furnace with Stoker	Uncontrolled	DeAngelis, 1979
$<$0.89[c]	Bituminous-washed	Warm Air Furnace with Stoker	Uncontrolled	DeAngelis, 1979

[a] NR = not reported.

[b] Average of two tests of the same boiler.

[c] Average of two tests of the same boiler. Both were less than the detection limit of 0.89 lb/10^{12} Btu.

TABLE C-60. MEASURED MANGANESE EMISSION FACTORS FOR PULVERIZED DRY BOTTOM UTILITY BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)			
Mean[a]	Range	Control Status	Reference
420[b]	---	ESP	Baig *et al.*, 1981
30.2	---	Wet Scrubber	Shih *et al.*, 1980b
886	---	Mechanical Ppt/ESP	Shih *et al.*, 1980b
393	---	Mechanical Ppt/ESP	Shih *et al.*, 1980b
2450[c]	286-9240	ESP	Evers *et al.*, 1980
3820[c]	2900-5280	Uncontrolled	Evers *et al.*, 1980
9300	---	Uncontrolled[d]	Sawyer and Higginbotham, 1981a
7000	---	Uncontrolled[e]	Sawyer and Higginbotham, 1981a
7700	---	Uncontrolled[e]	Sawyer and Higginbotham, 1981a
1300	---	ESP[d]	Sawyer and Higginbotham, 1981a
920	---	ESP[e]	Sawyer and Higginbotham, 1981a
740	---	ESP[e]	Sawyer and Higginbotham, 1981a
800	---	Uncontrolled[d]	Higginbotham and Goldberg, 1981
458[f]	300-640	Uncontrolled[e]	Higginbotham and Goldberg, 1981
160[g]	110-240	ESP[e]	Higginbotham and Goldberg, 1981
---	1180-1280	Uncontrolled	Scinto *et al.*, 1981
68	---	ESP	Scinto *et al.*, 1981
28	---	ESP/Scrubber	Scinto *et al.*, 1981
3790[h]	2570-4750	Mechanical Ppt.	Zielke and Bittman, 1982

TABLE C-60. MEASURED MANGANESE EMISSION FACTORS FOR PULVERIZED DRY BOTTOM UTILITY BOILERS FIRED WITH BITUMINOUS COAL (Continued)

Emission Factor ($lb/10^{12}$ Btu)			
Mean[a]	Range	Control Status	Reference
793[h]	570-1040	Mech. Ppt/1st ESP in Series of 2	Zielke and Bittman, 1982
149[i]	8.05-463	Mech. Ppt/2 ESPs in Series	Zielke and Bittman, 1982
88[j]	---	Venturi Scrubber	Ondov _et_ _al._, 1979a
53[j]	4.6-318	Venturi Scrubber	Ondov _et_ _al._, 1979a
36.5	---	Venturi Scrubber	Ondov _et_ _al._, 1979a
1.0[g]	0.97-1.1	ESP	Ondov _et_ _al._, 1979b
---	21.0-95.6[k]	ESP	Ondov _et_ _al._, 1979b
1630[g]	960-2690	Uncontrolled	Cowherd _et_ _al._, 1975
710[g]	460-1100	Mechanical Ppt.	Cowherd _et_ _al._, 1975

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[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single value was reported, it is included in this column.

[b] Average of six boilers.

[c] Average of eight tests of the same boiler.

[d] Tested while boiler was operating under baseline (design) conditions.

[e] Tested while boiler was operating under low-NO_x conditions - certain burners admit air rather than fuel, or different fuel/air ratios are admitted than under design operating conditions.

[f] Average of four tests of the same boiler.

[g] Average of three tests of the same boiler.

[h] Average of seven tests of the same boiler.

[i] Average of five tests of the same boiler.

[j] Same boiler tested at two different times.

[k] Range of six tests of the same boiler.

TABLE C-61. MEASURED MANGANESE EMISSION FACTORS FOR UTILITY PULVERIZED WET-BOTTOM BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Control Status	Reference
7.4	Mechanical Ppt/ESP	Shih *et al.*, 1980b
62.7	ESP	Shih *et al.*, 1980b
181	ESP	Shih *et al.*, 1980b
0.95	Venturi Wet Scrubber	Shih *et al.*, 1980b
214	ESP	Shih *et al.*, 1980b
418	ESP	Shih *et al.*, 1980b

TABLE C-62. MEASURED MANGANESE EMISSION FACTORS FOR UTILITY CYCLONE BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)			
Mean[a]	Range	Control Status	Reference
126	---	Wet Scrubber	Shih _et_ _al._, 1980b
170	---	ESP	Shih _et_ _al._, 1980b
314	---	ESP	Shih _et_ _al._, 1980b
53.5	---	ESP	Shih _et_ _al._, 1980b
182	---	ESP	Shih _et_ _al._, 1980b
1300[b]	1300-1300	Uncontrolled	Klein _et_ _al._, 1975b
36[b]	11-60	ESP	Klein _et_ _al._, 1975b

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[a] This column gives the arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single value was reported, it is included in this column.

[b] Average of two tests of the same boiler.

TABLE C-63. MEASURED MANGANESE EMISSION FACTORS FOR UTILITY STOKER BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Control Status	Reference
17.9	Fabric Filter	Shih *et al.*, 1980b
304	Mechanical Ppt.	Shih *et al.*, 1980b
188	Multiclone	Shih *et al.*, 1980b

TABLE C-64. MEASURED MANGANESE EMISSION FACTORS FOR UTILITY BOILERS FIRED WITH SUBBITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Boiler Type	Control Status	Reference
600	Cyclone	Uncontrolled	Leavitt *et al.*, 1979
120	Cyclone	Scrubber	Leavitt *et al.*, 1979
110	Pulverized	Venturi Scrubber	Radian, 1975
43	Pulverized	ESP	Radian, 1975
19	NR[a]	ESP	Mann *et al.*, 1978
35	NR	ESP	Mann *et al.*, 1978

[a] NR - not reported.

TABLE C-65. MEASURED MANGANESE EMISSION FACTORS FOR UTILITY BOILERS FIRED WITH LIGNITE COAL

Emission Factor (lb/10^{12} Btu)				
Mean[a]	Range	Boiler Type	Control Status	Reference
1680	---	Pulverized Dry Bottom	Multiclone	Shih *et al.*, 1980b
1560	---	Pulverized Dry Bottom	Multiclone	Shih *et al.*, 1980b
17.2	---	Pulverized Dry Bottom	ESP	Shih *et al.*, 1980b
10.9	---	Cyclone	ESP	Shih *et al.*, 1980b
1600	---	Cyclone	Cyclone	Radian, 1975
2.94[b]	2.92-2.96	Cyclone	ESP/Scrubber	Schock *et al.*, 1979
1790	---	Spreader Stoker	Multiclone	Shih *et al.*, 1980b
<10	---	Spreader Stoker	ESP	Shih *et al.*, 1980b

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only one value was reported, it is included in this column.

[b] Average of two tests of the same boiler.

TABLE C-66. MEASURED MANGANESE EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Emission Factor (lb/10^12 Btu) Mean[a]	Emission Factor (lb/10^12 Btu) Range	Boiler Type	Control Status	Reference
790[b]	---	Pulverized Dry Bottom	ESP	Baig et al., 1981
274	---	Pulverized Dry Bottom	ESP	Suprenant et al., 1980a
790	---	Pulverized Dry Bottom	Multiclone	Leavitt et al., 1978b; Fischer et al., 1979
14.6	---	Pulverized Dry Bottom	Multiclone/Scrubber	Leavitt et al., 1978b; Fischer et al., 1979
14.6	---	Pulverized Wet Bottom	Multiclone	Suprenant et al., 1980a
51.4	---	Spreader Stoker	Multiclone/ESP	Suprenant et al., 1980a
23.9	---	Spreader Stoker	Multiclone	Suprenant et al., 1980a
183	---	Spreader Stoker	Multiclone	Suprenant et al., 1980a
44[c]	30-58	Spreader Stoker	Uncontrolled[d]	Burlingame et al., 1981
767[e]	530-1100	Spreader Stoker	Uncontrolled[d]	Burlingame et al., 1981
14,000	---	Spreader Stoker	Uncontrolled[d]	Burlingame et al., 1981
135[c]	100-170	Spreader Stoker	Uncontrolled	Burlingame et al., 1981
345[c]	230-460	Spreader Stoker	Uncontrolled	Burlingame et al., 1981
870[c]	790-950	Spreader Stoker	Uncontrolled	Burlingame et al., 1981

TABLE C-66. MEASURED MANGANESE EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS (Continued)

Emission Factor (lb/10^{12} Btu)				
Mean[a]	Range	Boiler Type	Control Status	Reference
600	---	Overfeed Stoker	Uncontrolled	Burlingame _et al._, 1981
880	---	Overfeed Stoker	Uncontrolled	Burlingame _et al._, 1981
6,000[c]	5300-6700	Overfeed Stoker	Uncontrolled	Burlingame _et al._, 1981
230	---	Overfeed Stoker	Uncontrolled	Burlingame _et al._, 1981
2,050[c]	1100-3000	Overfeed Stoker	Economizer/Dust Collector	Burlingame _et al._, 1981
16	---	Spreader Stoker	Uncontrolled[f]	Lips and Higginbotham, 1981
12	---	Spreader Stoker	Mechanical Ppt/ESP[f]	Lips and Higginbotham, 1981
58	---	Spreader Stoker	Uncontrolled[g]	Lips and Higginbotham, 1981
9.1	---	Spreader Stoker	Mechanical Ppt/ESP[g]	Lips and Higginbotham, 1981

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Average for three boilers.

[c] Average of two tests of the same boiler.

[d] Traveling grate spreader stoker with re-injection from the dust collector. Measured upstream of control device.

[e] Average of three tests of the same boiler.

[f] Boiler operated under baseline (design) conditions.

[g] Boiler operated with low excess air level for NO_x control.

TABLE C-67. MEASURED MANGANESE EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Emission Factor ($lb/10^{12}$ Btu)				
Mean[a]	Range	Boiler Type	Control Status	Reference
15,500[b]	14,000-17,000	Spreader Stoker	Uncontrolled[c]	Burlingame *et al.*, 1981
9,950	---	Spreader Stoker	Uncontrolled[d]	Goldberg and Higginbotham, 1981
28	---	Spreader Stoker	Mechanical Ppt/ESP[d]	Goldberg and Higginbotham, 1981
1,300	---	Spreader Stoker	Uncontrolled[e]	Goldberg and Higginbotham, 1981
62	---	Spreader Stoker	Mechanical Ppt/ESP[e]	Goldberg and Higginbotham, 1981

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[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Mean of two tests of the same boiler.

[c] Traveling grate spreader stoker with re-injection from the dust collector. Measured upstream of controls.

[d] Tested while operating under baseline (design) conditions.

[e] Tested while operating under low-NO_x operating conditions - overfire air rate set at maximum level.

TABLE C-68. MEASURED MANGANESE EMISSION FACTORS FOR COMMERCIAL/INSTITUTIONAL COAL-FIRED BOILERS

Emission Factor $(\mathrm{lb}/10^{12}\ \mathrm{Btu})$	Type of Coal	Boiler Type	Control Status	Reference
2680	Bituminous	Pulverized Dry Bottom	Uncontrolled	Suprenant *et al.*, 1980b
25.6	Bituminous	Pulverized Dry Bottom	Multiclone/Scrubber	Suprenant *et al.*, 1980b
3.5	Bituminous	Underfeed Stoker	Uncontrolled	Suprenant *et al.*, 1980b
188	Bituminous	Spreader Stoker	Mechanical Ppt.	Suprenant *et al.*, 1980b
290	Bituminous	Overfeed Stoker	Mechanical Ppt.	Suprenant *et al.*, 1980b
39.5	Anthracite	Stoker	Uncontrolled	Suprenant *et al.*, 1980b
163	Anthracite	Stoker	Uncontrolled	Suprenant *et al.*, 1980b
138	Anthracite	Stoker	Uncontrolled	Suprenant *et al.*, 1980b

TABLE C-69. MEASURED MANGANESE EMISSION FACTORS FOR COAL-FIRED RESIDENTIAL FURNACES

Emission Factor ($lb/10^{12}$ Btu)	Coal Type	Furnace Type	Control Status	Reference
155	Bituminous	NR[a]	Uncontrolled	DeAngelis and Reznik, 1979
3640	Bituminous	NR	Uncontrolled	DeAngelis and Reznik, 1979
44.5[b]	Bituminous	Warm Air Furnace with Stoker	Uncontrolled	DeAngelis, 1979
89[b]	Bituminous-washed	Warm Air Furnace with Stoker	Uncontrolled	DeAngelis, 1979

[a] NR = not reported.

[b] Average of two tests of the same boiler.

TABLE C-70. MEASURED NICKEL EMISSION FACTORS FOR PULVERIZED DRY BOTTOM UTILITY BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu) Mean[a]	Emission Factor ($lb/10^{12}$ Btu) Range	Control Status	Reference
2,600[b,c]	---	ESP	Baig *et al.*, 1981
104	---	Wet Scrubber	Shih *et al.*, 1980b
5,760[c]	---	Mechanical Ppt/ESP	Shih *et al.*, 1980b
4,480[c]	---	Mechanical Ppt/ESP	Shih *et al.*, 1980b
1,600	---	ESP[d]	Sawyer and Higginbotham, 1981a
1,100	---	ESP[e]	Sawyer and Higginbotham, 1981a
5,000	---	Uncontrolled[d]	Sawyer and Higginbotham, 1981a
1,500	---	Uncontrolled[e]	Sawyer and Higginbotham, 1981a
700	---	ESP[d]	Higginbotham and Goldberg, 1981
1,400	---	Uncontrolled[d]	Higginbotham and Goldberg, 1981
913[f]	520-1,400	ESP[e]	Higginbotham and Goldberg, 1981
1,400[f]	1,100-1,600	Uncontrolled[e]	Higginbotham and Goldberg, 1981
430	---	Uncontrolled	Scinto *et al.*, 1981
12.2	12.1-12.4	ESP/Scrubber	Scinto *et al.*, 1981
15,300[g]	8,030-23,500	Mechanical Ppt.	Zielke and Bittman, 1982
2,550[h]	1,010-4,870	Mech. Ppt/1st ESP in Series of 2	Zielke and Bittman, 1982
360[i]	132-724	Mech. Ppt/ 2 ESPs in Series	Zielke and Bittman, 1982
35[j]	---	Venturi Scrubber	Ondov, 1979a

TABLE C-70. MEASURED NICKEL EMISSION FACTORS FOR PULVERIZED DRY BOTTOM UTILITY BOILERS FIRED WITH BITUMINOUS COAL (Continued)

Emission Factor ($lb/10^{12}$ Btu)			
Mean[a]	Range	Control Status	Reference
30[j]	12-94	Venturi Scrubber	Ondov, 1979a
840[f]	690-1,100	Uncontrolled	Cowherd *et al.*, 1975
440[f]	260-720	Mechanical Ppt.	Cowherd *et al.*, 1975

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single value was reported, it is included in this column.

[b] Average of tests of six boilers.

[c] Reference noted that corrosion of sampling train components may account for higher than expected nickel emissions measurements.

[d] Tested while boiler was operating under baseline (design) conditions.

[e] Tested while boiler was operating under low-NO_x conditions - certain burners admit air rather than fuel, or different fuel/air ratios are admitted than under design operating conditions.

[f] Average of three tests of the same boiler.

[g] Average of seven tests of the same boiler.

[h] Average of six tests of the same boiler.

[i] Average of four tests of the same boiler.

[j] Tests of the same boiler during two different time periods.

TABLE C-71. MEASURED NICKEL EMISSION FACTORS FOR UTILITY PULVERIZED WET BOTTOM BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Control Status	Reference
74.4	Mechanical Ppt/ESP	Shih *et al.*, 1980b
372[a]	ESP	Shih *et al.*, 1980b
1470[a]	ESP	Shih *et al.*, 1980b
1.1	Venturi Scrubber	Shih *et al.*, 1980b
1850[a]	ESP	Shih *et al.*, 1980b
2550[a]	ESP	Shih *et al.*, 1980b

[a] Reference noted that corrosion of sampling train components may account for higher than expected nickel emissions measurements.

TABLE C-72. MEASURED NICKEL EMISSION FACTORS FOR UTILITY CYCLONE BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Control Status	Reference
46.5	Wet Scrubber	Shih *et al.*, 1980b
997[a]	ESP	Shih *et al.*, 1980b
2000[a]	ESP	Shih *et al.*, 1980b
2020[a]	ESP	Shih *et al.*, 1980b
1330[a]	ESP	Shih *et al.*, 1980b
960	Uncontrolled	Klein *et al.*, 1975b; Lyon, 1977
4.6	ESP	Klein *et al.*, 1975b; Lyon, 1977

[a] Reference noted that corrosion of sampling train components may account for higher than expected nickel emissions measurements.

TABLE C-73. MEASURED NICKEL EMISSION FACTORS FOR UTILITY STOKER BOILERS FIRED WITH BITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Control Status	Reference
165	Fabric Filter	Shih *et al.*, 1980b
5180[a]	Mechanical Ppt.	Shih *et al.*, 1980b
1330[a]	Multiclone	Shih *et al.*, 1980b

[a] Reference noted that corrosion of sampling train components may account for higher than expected nickel emission measurements.

TABLE C-74. MEASURED NICKEL EMISSION FACTORS FOR UTILITY BOILERS FIRED WITH SUBBITUMINOUS COAL

Emission Factor ($lb/10^{12}$ Btu)	Boiler Type	Control Status	Reference
1700	Cyclone	Uncontrolled	Leavitt, 1979
46	Cyclone	Scrubber	Leavitt, 1979
50	Pulverized	Scrubber	Radian, 1975
70	Pulverized	ESP	Radian, 1975
5.4	NR[a]	ESP	Mann *et al.*, 1978
21	NR	ESP	Mann *et al.*, 1978

[a] NR - not reported.

TABLE C-75. MEASURED NICKEL EMISSION FACTORS FOR UTILITY BOILERS FIRED WITH LIGNITE COAL

Emission Factor (lb/10^{12} Btu)	Boiler Type	Control Status	Reference
611[a]	Pulverized Dry Bottom	Multiclone	Shih *et al.*, 1980b
267[a]	Pulverized Dry Bottom	Multiclone	Shih *et al.*, 1980b
<158	Pulverized Dry Bottom	ESP	Shih *et al.*, 1980b
<109	Cyclone	ESP	Shih *et al.*, 1980b
740	Cyclone	Cyclone	Radian, 1975
641[a]	Spreader Stoker	Multiclone	Shih *et al.*, 1980b
<88	Spreader Stoker	ESP	Shih *et al.*, 1980b

[a] Reference noted that corrosion of sampling train components may account for higher than expected nickel emissions measurements.

TABLE C-76. MEASURED NICKEL EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Emission Factor (lb/10^{12} Btu) Mean[a]	Range	Boiler Type	Control Status	Reference
930[b,c]	---	Pulverized Dry Bottom	ESP	Baig et al., 1981
10.0	---	Pulverized Dry Bottom	ESP	Suprenant et al., 1980a
1,390	---	Pulverized Dry Bottom	Multiclone	Leavitt et al., 1978b; Fischer et al, 1979
60	---	Pulverized Dry Bottom	Multiclone/Scrubber	Leavitt et al., 1978b; Fischer et al., 1979
36	---	Pulverized Wet Bottom	Multiclone	Suprenant et al., 1980a
1,020[c]	---	Spreader Stoker	Multiclone/ESP	Suprenant et al., 1980a
31	---	Spreader Stoker	Multiclone	Suprenant et al., 1980a
230	---	Spreader Stoker	Multiclone	Suprenant et al., 1980a
70[d]	32-107	Spreader Stoker	Uncontrolled[e]	Burlingame et al., 1981
16,300[f]	14,200-20,600	Spreader Stoker	Uncontrolled[e]	Burlingame et al., 1981
10,200	---	Spreader Stoker	Uncontrolled[e]	Burlingame et al., 1981
775[d]	650-900	Spreader Stoker	Uncontrolled	Burlingame et al., 1981
4,100[d]	2,200-6,000	Spreader Stoker	Uncontrolled	Burlingame et al., 1981
3,200[d]	2,000-4,400	Spreader Stoker	Uncontrolled	Burlingame et al., 1981

TABLE C-76. MEASURED NICKEL EMISSION FACTORS FOR BITUMINOUS COAL-FIRED INDUSTRIAL BOILERS (Continued)

Emission Factor ($lb/10^{12}$ Btu)				
Mean[a]	Range	Boiler Type	Control Status	Reference
840	---	Overfeed Stoker	Uncontrolled	Burlingame *et al.*, 1981
3,000	---	Overfeed Stoker	Uncontrolled	Burlingame *et al.*, 1981
12,300[d]	1,600-23,000	Overfeed Stoker	Uncontrolled	Burlingame *et al.*, 1981
2,300	---	Overfeed Stoker	Uncontrolled	Burlingame *et al.*, 1981
22,200[d]	16,500-28,000	Overfeed Stoker	Economizer/Dust Collector	Burlingame *et al.*, 1981

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[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Average for three boilers.

[c] Reference noted that corrosion of sampling train components may explain higher than expected nickel emissions measurements.

[d] Average of two tests of the same boiler.

[e] Traveling grate spreader stoker with re-injection from the dust collector. Measured upstream of control device.

[f] Average of three tests of the same boiler.

TABLE C-77. MEASURED NICKEL EMISSION FACTORS FOR SUBBITUMINOUS COAL-FIRED INDUSTRIAL BOILERS

Emission Factor (lb/10^{12} Btu)				
Mean[a]	Range	Boiler Type	Control Status	Reference
3900[b]	1300-6500	Spreader Stoker	Uncontrolled[c]	Burlingame _et al._, 1981
840	---	Spreader Stoker	Uncontrolled	Goldberg and Higginbotham, 1981
30	---	Spreader Stoker	Mechanical Ppt/ESP	Goldberg and Higginbotham, 1981

[a] This column gives arithmetic mean values for each boiler tested. Footnotes indicate how many measurements each mean represents, if this information was included in the reference. If only a single measurement was reported, it is included in this column.

[b] Mean of two tests of the same boiler.

[c] Traveling grate spreader stoker with re-injection from the dust collector. Measured upstream of controls.

TABLE C-78. MEASURED NICKEL EMISSION FACTORS FOR COMMERCIAL/INSTITUTIONAL COAL-FIRED BOILERS

Emission Factor ($lb/10^{12}$ Btu)	Type of Coal	Boiler Type	Control Status	Reference
2430	Bituminous	Pulverized Dry Bottom	Uncontrolled	Suprenant *et al.*, 1980b
309	Bituminous	Pulverized Dry Bottom	Multiclone/Scrubber	Suprenant *et al.*, 1980b
30	Bituminous	Underfeed Stoker	Uncontrolled	Suprenant *et al.*, 1980b
91	Bituminous	Spreader Stoker	Mechanical Ppt.	Suprenant *et al.*, 1980b
1530	Bituminous	Overfeed Stoker	Mechanical Ppt.	Suprenant *et al.*, 1980b
314	Anthracite	Stoker	Uncontrolled	Suprenant *et al.*, 1980b
1070	Anthracite	Stoker	Uncontrolled	Suprenant *et al.*, 1980b
1090	Anthracite	Stoker	Uncontrolled	Suprenant *et al.*, 1980b

TABLE C-79. MEASURED NICKEL EMISSION FACTORS FOR COAL-FIRED RESIDENTIAL FURNACES

Emission Factor ($lb/10^{12}$ Btu)	Coal Type	Furnace Type	Control Status	Reference
3.9	Bituminous	NR[a]	Uncontrolled	DeAngelis and Reznik, 1979
1550	Bituminous	NR	Uncontrolled	DeAngelis and Reznik, 1979
534[b]	Bituminous	Warm Air Furnace with Stoker	Uncontrolled	DeAngelis, 1979
3030[b]	Bituminous-washed	Warm Air Furnace with Stoker	Uncontrolled	DeAngelis, 1979

[a] NR = not reported.

[b] Average of two tests of the same boiler.

TABLE C-80. MEASURED URANIUM-238 EMISSION FACTORS FOR COAL-FIRED UTILITY BOILERS

Emission Factor[a]					
pCi/g	pCi/10^6 Btu	Coal Type	Boiler Type	Control Status	Reference
37.5	3214.3	Subbituminous	Cyclone	Scrubber	Roeck *et al.*, 1983
5.6	73.7	Lignite	Pulverized Dry Bottom	Cyclone/Scrubber	Roeck *et al.*, 1983
4.2	350.5	Lignite	Pulverized Dry Bottom	ESP	Roeck *et al.*, 1983
7.1	22.5	Lignite	Pulverized Dry Bottom	ESP/Scrubber	Roeck *et al.*, 1983
0.5	13.8	Lignite	Stoker	Cyclone/ESP	Roeck *et al.*, 1983
9.2	675.9	Bituminous[b]	Pulverized Dry Bottom	ESP	Roberson and Eggleston, 1983
7.6	210.4	Bituminous[b]	Pulverized Dry Bottom	ESP	Roberson and Eggleston, 1983
7	6.3	Bituminous[b]	Pulverized Dry Bottom	ESP	Roberson and Eggleston, 1983
4.4	227.5	Bituminous[b]	Pulverized Dry Bottom	ESP	Roberson and Eggleston, 1983
3.0	68.0	Bituminous[b]	Cyclone	ESP	Roberson and Eggleston, 1983
3.3	248.4	Bituminous[b]	Pulverized Dry Bottom	ESP	Roberson and Eggleston, 1983
4.1	301.2	Bituminous[b]	Cyclone	Scrubber	Roberson and Eggleston, 1983
7.2	486.5	Bituminous[b]	NR[c]	ESP	Roberson and Eggleston, 1983
7	101.6	Bituminous[b]	NR	ESP	Roberson and Eggleston, 1983
8.6[d]	511.5[d]	Bituminous[b]	Pulverized Dry Bottom	ESP	Roberson and Eggleston, 1983
8.1	482.5	Bituminous[b]	Pulverized Dry Bottom	ESP	Roberson and Eggleston, 1983

TABLE C-80. MEASURED URANIUM-238 EMISSION FACTORS FOR COAL-FIRED UTILITY BOILERS (Continued)

Emission Factor[a]					
pCi/g	pCi/10^6 Btu	Coal Type	Boiler Type	Control Status	Reference
34.2	---	NR	---	ESP	Coles *et al.*, 1978
0.017	---	NR	Cyclone	Scrubber	Office of Radiation Programs, 1979
0.005	---	NR	Cyclone	ESP	Office of Radiation Programs, 1979
0.004	---	NR	Pulverized, Slag Bottom	Mech. Ppt/ESP	Office of Radiation Programs, 1979
0.003	---	NR	Stoker	Fabric Filter	Office of Radiation Programs, 1979

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[a] Where heating values were available from the reference, emission factors expressed as pCi/g were converted to pCi/10^6 Btu heat input.

[b] Reference specified that all plants tested were burning bituminous and/or subbituminous coals.

[c] NR = not reported.

[d] Average of three tests on one unit.

TABLE C-81. MEASURED THORIUM-232 EMISSION FACTORS FOR COAL-FIRED UTILITY BOILERS

Emission Factor[a]					
pCi/g	pCi/10^6 Btu	Coal Type	Boiler Type	Control Status	Reference
2.8[b]	171.2[b]	NR[c]	Pulverized Dry Bottom	ESP	Roberson and Eggleston, 1983
2.8[b]	167.8[b]	NR	Pulverized Dry Bottom	ESP	Roberson and Eggleston, 1983
2.68	229.7	Subbituminous	Cyclone	Scrubber	Roeck et al., 1983
2.78	36.5	Lignite	Pulverized Dry Bottom	Cyclone/Scrubber	Roeck et al., 1983
0.60	50.3	Lignite	Pulverized Dry Bottom	ESP	Roeck et al., 1983
7.14	22.7	Lignite	Pulverized Dry Bottom	ESP/Scrubber	Roeck et al., 1983
0.5	13.8	Lignite	Stoker	Cyclone/ESP	Roeck et al., 1983
1.9	360	Bituminous[d]	Pulverized Dry Bottom	ESP	Roberson and Eggleston, 1983
5.3	146.6	Bituminous[d]	Pulverized Dry Bottom	ESP	Roberson and Eggleston, 1983
12[e]	10.9	Bituminous[d]	Pulverized Dry Bottom	ESP	Roberson and Eggleston, 1983
2.2	113.7	Bituminous[d]	Pulverized Dry Bottom	ESP	Roberson and Eggleston, 1983
1.8	40.8	Bituminous[d]	Cyclone	ESP	Roberson and Eggleston, 1983
2.4	180.7	Bituminous[d]	Pulverized Dry Bottom	ESP	Roberson and Eggleston, 1983
1.5	110.2	Bituminous[d]	Cyclone	Scrubber	Roberson and Eggleston, 1983

[a] Where heating values were available from the reference, emission factors expressed as pCi/g particulate emissions were converted to pCi/10^6 Btu heat input.

[b] Average of three tests on one unit.

[c] NR = not reported.

[d] Reference specified that all plants tested were burning bituminous and/or subbituminous coal.

[e] Reference noted that error may be $\geq$30 percent. Not used in calculation of mean or range.

TABLE C-82. TOTAL POM EMISSIONS FROM PULVERIZED COAL-FIRED UTILITY BOILERS

Boiler Characteristics	Coal Type	Controls Used	Total POM Emission Factor lb/10^{12} Btu-Heat Input	Reference
Horizontally Opposed	[a]	[a]	0.03 - 4.5[b,c]	Barrett *et al.*, 1983
Front Wall-Fired	[a]	[a]	1.1[b,d]	Barrett *et al.*, 1983
Corner Fired	[a]	[a]	2.2 - 2.7[b,e]	Barrett *et al.*, 1983
Vertically-Fired	[a]	[a]	0.32 - 1.6[b,f]	Barrett *et al.*, 1983
Dry Bottom	[a]	[a]	0.8[g]	Hangebrauck *et al.*, 1964
Tangentially-Fired	Subbituminous	ESP	0.7[h]	Haile *et al.*, 1983
Vertically-Fired	Bituminous	ESP	6.5[h]	Haile *et al.*, 1983
Front Wall-Fired	Bituminous	ESP	1.7[i]	Haile *et al.*, 1983
Dry Bottom	Bituminous	Wet Scrubber	8.55[j,k]	Shih *et al.*, 1980b
Dry Bottom	Bituminous	Multicyclone/ESP	0.033[j,l]	Shih *et al.*, 1980b
Dry Bottom	Bituminous	Multicyclone/ESP	18.6[j,m]	Shih *et al.*, 1980b
Wet Bottom	Bituminous	ESP	18.6[j,n]	Shih *et al.*, 1980b
Wet Bottom	Bituminous	Wet Scrubber	565[j,o]	Shih *et al.*, 1980b
Dry Bottom, Front Wall-Fired	Lignite	Multicyclones	18.3[j,p]	Shih *et al.*, 1980b
Dry Bottom, Front Wall-Fired	Lignite	Multicyclones	1.8[j,p]	Shih *et al.*, 1980b
Dry Bottom, Front Wall-Fired	Lignite	ESP	2.6[j,p]	Shih *et al.*, 1980b
Dry Bottom, Vertically-Fired	[a]	None	0.75 - 9.7[q,r]	Hangebrauck *et al.*, 1967
Dry Bottom, Vertically-Fired	[a]	Multicyclone/ESP	0.7 - 1.6[q,s]	Hangebrauck *et al.*, 1967
Dry Bottom, Front Wall-Fired	[a]	ESP	0.4 - 1.4[q,t]	Hangebrauck *et al.*, 1967
Dry Bottom, Tangentially-Fired	[a]	Multicyclone/ESP	2.2[q,u]	Hangebrauck *et al.*, 1967
Wet Bottom, Opposed-Fired	[a]	Multicyclones	0.8 - 4.6[q,v]	Hangebrauck *et al.*, 1967

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[a] Data not reported in available literature.

[b] Factor represents only particulate POM emissions.

TABLE C-82. TOTAL POM EMISSIONS FROM PULVERIZED COAL-FIRED UTILITY BOILERS (Continued)

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[c] Specific POM compounds identified in these emissions include benzo(a)pyrene, benzo(g,h,i)perylene, coronene, 7,12-dimethyl benz(a)anthracene, fluoranthene, 3-methylcholanthrene, benzo(e)pyrene, and pyrene.

[d] The primary constituents of total POM emissions were benzo(e)pyrene (45 percent), pyrene (35 percent), fluoranthene (16 percent), benzo(a)pyrene (4 percent), and benzo(g,h,i)perylene (1 percent).

[e] Specific POM compounds identified in these emissions include anthanthrene, anthracene, benz(a)anthracene, benzo(a)pyrene, benzo(e)pyrene, benzo(g,h,i)perylene, coronene, fluoranthene, perylene, phenanthrene, and pyrene. The primary constituents of total POM emissions were fluoranthene (33-40 percent), benzo(g,h,i)perylene (12-15 percent), pyrene (12-14 percent), and benzo(a)pyrene (12-14 percent).

[f] Specific POM compounds identified in these emissions include benz(a)anthracene, benzo(a)pyrene, benzo(e)pyrene, benzo(g,h,i)perylene, fluoranthene, perylene, phenanthrene, and pyrene. The principal constituents of total POM emissions were fluoranthene (36-53 percent), pyrene (22-42 percent), and benzo(a)pyrene (3-17 percent).

[g] Factor represents predominantly particulate POM. Eleven specific POM compounds were analyzed for during these tests. Specific compounds identified were pyrene, benzo(a)pyrene, benzo(e)pyrene, fluoranthene, and benz(a)anthracene. Pyrene and fluoranthene accounted for 90 percent of total POM emissions.

[h] Factor represents both particulate and gaseous POM. Nine specific POM compounds were analyzed for during these tests. Specific compounds identified were naphthalene, acenaphthylene, fluorene, phenanthrene, fluoranthene, pyrene, chrysene, and benzo(a)pyrene. Naphthalene and phenanthrene accounted for 85 percent of total POM emissions. Factor represents average of five tests of the same boiler.

[i] Factor represents both particulate and gaseous POM. Nine specific POM compounds were analyzed for during these tests. Specific compounds identified were naphthalene, fluorene, phenanthrene, fluoranthene, and chrysene. Naphthalene and phenanthrene accounted for about 91 percent of total POM emissions. Factor represents average of five tests of the same boiler.

[j] Factor represents both particulate and gaseous POM. Fifty-six specific POM compounds were analyzed for during these tests.

[k] Specific compounds identified were biphenyl, benzo(g,h,i)perylene, o-phenylenepyrene, dibenz(a,h)anthracene, picene, and dibenz(a,c)anthracene. Benzo(g,h,i)perylene, o-phenylenepyrene, and dibenz(a,h)anthracene accounted for about 82 percent of total POM emissions.

[l] Specific compounds identified were phenyl naphthalene and biphenyl, with phenyl naphthalene constituting 66 percent of total POM emissions.

[m] Specific compounds identified were naphthalene and biphenyl, with naphthalene constituting 90 percent of total POM emissions.

[n] Specific compounds identified were naphthalene and phenanthrene, with naphthalene constituting 73 percent of total POM emissions.

[o] Specific compounds identified were naphthalene, biphenyl, phenanthrene, pyrene, fluoranthene, chrysene, benzo(a)pyrene, benzo(e)pyrene, benzo(b)fluoranthene, benzo(g,h,i)perylene, and indeno(1,2,3-c,d)pyrene. Total POM emissions consisted primarily of naphthalene (26 percent), phenanthrene (23 percent), pyrene (16 percent), and chrysene (10 percent).

[p] Reported value is for trimethyl propenyl naphthalene.

[q] Factor represents predominantly particulate POM. Ten specific POM compounds were analyzed for during these tests.

[r] Specific compounds identified were benzo(a)pyrene, pyrene, benzo(g,h,i)perylene, anthanthrene, fluoranthene, benzo(e)pyrene, perylene, coronene, anthracene, and phenanthrene. Fluorene, phenanthrene, and pyrene were generally the predominant POM compounds measured.

[s] Specific compounds identified were benzo(a)pyrene, pyrene, fluoranthene, benzo(e)pyrene, perylene, and benzo(g,h,i)perylene. Pyrene and fluoranthene were generally the dominant POM compounds measured. However, in one test, total POM emissions consisted of the following distribution: benzo(a)pyrene (27 percent), fluoranthene (18 percent), benzo(e)pyrene (17 percent), benzo(g,h,i)perylene (18 percent), and pyrene (16 percent).

[t] Specific compounds identified were benzo(a)pyrene, pyrene, benzo(e)pyrene, benzo(g,h,i)perylene, phenanthrene, and fluoranthene. Pyrene, phenanthrene, and fluoranthene accounted for the majority of total POM emissions.

[u] Specific compounds identified were benzo(a)pyrene, pyrene, benzo(e)pyrene, perylene, benzo(g,h,i)perylene, anthanthrene, coronene, phenanthrene, and fluoranthrene. Fluoranthene, pyrene, benzo(a)pyrene, and benzo(g,h,i)perylene accounted for 80 percent of total POM emissions.

[v] Specific compounds identified were benzo(a)pyrene, pyrene, fluoranthene, coronene, benzo(g,h,i)perylene, and benzo(e)pyrene. Benzo(g,h,i)-perylene, fluoranthene, and benzo(e)pyrene were the compounds generally constituting the majority of total POM emissions.

TABLE C-83. TOTAL POM EMISSIONS FROM CYCLONE COAL-FIRED UTILITY BOILERS

Coal Type	Controls Used	Total POM Emission Factor $lb/10^{12}$ Btu-heat Input	Reference
a	ESP	1.2 - 7.4[b]	Hangebrauck *et al.*, 1967
a	a	4.3[c]	Barrett *et al.*, 1983
Bituminous	ESP	2.04[d]	Haile *et al.*, 1983
Bituminous	ESP	0.46[d]	Haile *et al.*, 1983
Bituminous	ESP	57.2[e,f]	Shih *et al.*, 1980b
Bituminous	ESP	2.7[e,g]	Shih *et al.*, 1980b
Lignite	ESP	0.11[e,h]	Shih *et al.*, 1980b
Lignite	ESP	1.6[e,i]	Shih *et al.*, 1980b
Bituminous	ESP	5.6[e,j]	Shih *et al.*, 1980b
Bituminous	Wet Scrubber	16.2[e,k]	Shih *et al.*, 1980b

[a] Data were not reported in the available literature.

[b] Factor represents predominantly particulate POM emissions. Ten specific POM compounds were analyzed for during these tests. Specific compounds identified were benzo(a)pyrene, pyrene, benzo(e)pyrene, perylene, benzo(g,h,i)perylene, coronene, and fluoranthene. Pyrene, benzo(e)pyrene, benzo(a)pyrene, and benzo(g,h,i)perylene accounted for the majority of total POM emissions.

[c] Factor represents only particulate POM emissions. The principal constituents of total POM emissions were pyrene (53 percent), benzo(e)pyrene (20 percent), benzo(a)pyrene (11 percent), benzo(g,h,i)perylene (10 percent), and fluoranthene (4 percent).

[d] Factor represents both particulate and gaseous POM emissions. Nine specific POM compounds were analyzed for during these tests. Specific compounds identified were naphthalene, fluorene, phenanthrene, and chrysene. Naphthalene constituted from 90 to 99 percent of total POM emissions. Factor represents the mean of five tests of the same boiler.

[e] Factor represents both particulate and gaseous POM emissions. Fifty-six specific POM compounds were analyzed for during these tests.

TABLE C-83. TOTAL POM EMISSIONS FROM CYCLONE COAL-FIRED UTILITY BOILERS (Continued)

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[f] Reported value is for naphthalene. No other POM compounds were detected.

[g] Reported value is for phenyl naphthalene. No other POM compounds were detected.

[h] Reported value is for biphenyl. No other POM compounds were detected.

[i] Reported value is for trimethyl propenyl naphthalene. No other POM compounds were detected.

[j] Specific compounds identified were ethyl biphenyl, phenanthrene, and methylphenthrene. Methylphenthrene constituted 84 percent of total POM emissions.

[k] Specific compounds identified were biphenyl, decahydronaphthalene, ditertbutyl naphthalene, dimethyl isopropyl naphthalene, hexamethyl biphenyl, hexamethyl hexahydro indacene, dihydronaphthalene, C_{10} substituted naphthalene, C_{10} substituted decahydronaphthalene, methyl naphthalene, anthracene/phenanthrene, 9,10-dihydronaphthalene/1-1' diphenylethene, 1,1'-bis (p-ethylphenyl)-ethane/tetramethyl biphenyl, 5-methyl-benz-c-acridine, and 2,3-dimethyl decahydronaphthalene. Biphenyl, 1,1-bis(p-ethylphenyl)-ethane/tetramethyl biphenyl, and methyl naphthalene constitute almost 80 percent of total POM emissions.

TABLE C-84. TOTAL POM EMISSIONS FROM STOKER COAL-FIRED UTILITY BOILERS

Boiler Characteristics	Coal Type	Controls Used	Total POM Emission Factor lb/10^{12} Btu-heat Input	Reference
Spreader, Traveling Grate	a	Multicyclones	0.13 - 0.47^{b}	Hangebrauck et al., 1967
Chain Grate	a	a	114^{c}	Barrett et al., 1983
Spreader	a	a	0.46^{d}	Barrett et al., 1983
Chain Grate	a	a	2.7^{e}	Hangebrauck et al., 1964
a	Bituminous	Baghouse	92.1^{f,g}	Shih et al., 1980b
a	Bituminous	Multicyclones	12.0^{f,h}	Shih et al., 1980b
Spreader	Lignite	Multicyclones	14.6^{f,i}	Shih et al., 1980b

[a] Data not reported in the available literature.

[b] Factor represents primarily particulate POM emissions. Ten specific POM compounds were analyzed for during these tests. Specific compounds identified were benzo(a)pyrene, pyrene, benzo(e)pyrene, coronene, and fluoranthene. Pyrene, fluoranthene, and benzo(e)pyrene constitute the majority of total POM emissions.

[c] Factor represents only particulate POM emissions. The primary constituents of total POM emissions were fluoranthene (30 percent), pyrene (22 percent), phenanthrene (22 percent), benzo(a)pyrene (15 percent), benzophenanthrene (5 percent), and 1,2-benzofluorene (4 percent).

[d] Factor represents only particulate POM emissions. The primary constituents of total POM emissions were pyrene (50 percent), fluoranthene (24 percent), benzo(e)pyrene (14 percent), benzo(a)pyrene (<10 percent), and coronene (3 percent).

[e] Factor represents primarily particulate POM emissions. Eleven specific POM compounds were analyzed for during these tests. Specific compounds identified were benzo(a)pyrene, pyrene, benzo(e)pyrene, and fluoranthene. Fluoranthene and pyrene accounted for about 87 percent of total POM emissions.

[f] Factor represents both particulate and gaseous POM emissions. Fifty-six specific POM compounds were analyzed for during these tests.

[g] Specific compounds identified were naphthalene and a mixture of 3,8-dimethyl-5-(1-methyl ethyl)-1,2-naphthalene dione and trimethyl naphthalene. The naphthalene mixture constituted 97 percent of total POM emissions.

[h] Specific compounds identified were naphthalene, phenyl naphthalene, and 2-ethyl-1,1'-biphenyl. Phenyl naphthalene and 2-ethyl-1,1'-bipheny constituted 96 percent of total POM emissions.

[i] Reported value is for trimethyl propenyl naphthalene. No other POM compounds were detected.

TABLE C-85. MEASURED TOTAL POM EMISSION FACTORS FOR PULVERIZED COAL-FIRED INDUSTRIAL BOILERS

Boiler Characteristics	Coal Type	Controls Used	Total POM Emission Factor lb/10^{12} Btu-heat Input	Reference
Dry Bottom, Watertube	Bituminous	Multicyclones	2.8[a]	Hangebrauck _et al._, 1964
Watertube	Bituminous	ESP	68.0[b]	Suprenant _et al._, 1980a
Wet Bottom	Bituminous	Cyclones/ESP	6.6[c]	Suprenant _et al._, 1980a
Dry Bottom, Horizontally-Fired	Bituminous	ESP	121[d]	McCurley _et al._, 1979

[a] Factor represents primarily particulate POM emissions. Eleven specific POM compounds were analyzed for during these tests. Specific compounds identified were benzo(a)pyrene, pyrene, benzo(e)pyrene, anthracene, and fluoranthene. Fluoranthene, anthracene, and pyrene accounted for 90 percent of total POM emissions.

[b] Factor represents both particulate and gaseous POM emissions. Specific compounds identified were anthracene/phenanthrene, fluoranthene, dibenzothiophene, methylanthracenes/phenanthrenes, dimethylanthracenes/phenanthrenes, methylfluoranthenes/pyrenes, benzo(c)phenanthrene, dimethylbenz(a)anthracenes, methylcholanthrenes, indeno(1,2,3-c,d)pyrene, benzofluoranthenes, dibenz(a,h)anthracene, dibenzopyrenes, and methylchrysenes. The primary constituents of total POM emissions are benzofluoranthenes (38 percent), fluoranthene (18 percent), anthracene/phenanthrene (18 percent), and methylcholanthrenes (10 percent).

[c] Factor represents both particulate and gaseous POM emissions. Fifty-six specific POM compounds were analyzed for during these tests. Specific compounds identified were biphenyl, phenanthrene, pyrene, naphthalene, and benzo(g,h,i)perylene. Phenanthrene and naphthalene constituted 93 percent of total POM emissions.

[d] Factor represents both particulate and gaseous POM emissions. Specific compounds identified were dibenzothiophene, anthracene/phenanthrene, methylanthracenes/phenanthrenes, dimethylanthracenes/phenanthrenes, fluoranthene, pyrene, methyl fluoranthenes/pyrenes, benzo(c)phenanthrene, chrysene/benz(a)anthracene, dimethylbenz(a)anthracenes, benzofluoranthenes, benzopyrenes/perylene, methylcholanthrenes, indeno(1,2,3-c,d)-pyrene, dibenz(a,h)anthracene, dibenzo(c,g)carbazole, dibenzopyrenes, methylchrysenes, anthracene/benzo(g,h,i)perylene. The primary constituents of total POM emissions are chrysene/benz(a)anthracene (41 percent), benzofluoranthenes (22 percent), fluoranthene (11 percent), and anthracene/phenanthrene (11 percent).

TABLE C-86. MEASURED TOTAL POM EMISSION FACTORS FOR STOKER COAL-FIRED INDUSTRIAL BOILERS

Characteristics	Coal Type	Controls Used	Total POM Emission Factor lb/10^{12} Btu-heat Input	Reference
Spreader Stoker	a	Multicyclones	2.97[b,c]	Hangebrauck *et al.*, 1964
Underfeed Stoker	a	None	197[b,d]	Hangebrauck *et al.*, 1964
Chain Grate Stoker	a	None	2.7[b,e]	Hangebrauck *et al.*, 1964
Spreader Stoker	Bituminous	Cyclones/ESP	413[f]	Suprenant *et al.*, 1980
Spreader Stoker	Bituminous/ Subbituminous	None	13.7[g,h]	Burlingame *et al.*, 1981
Spreader Stoker	Bituminous	None	10.0[g,i]	Burlingame *et al.*, 1981
Mass-Fired Overfeed Stoker	Bituminous	None	32.9[g,j]	Burlingame *et al.*, 1981

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[a] Data not reported in the available literature.

[b] Factor represents primarily particulate POM emissions. Eleven specific POM compounds were analyzed for during these tests.

[c] Specific compounds identified were benzo(a)pyrene, pyrene, benzo(e)pyrene, coronene, and fluoranthene. Pyrene, benzo(e)pyrene, and fluoranthene constitute 96 percent of total POM emissions.

[d] Specific compounds identified were benzo(a)pyrene, pyrene, benzo(e)pyrene, perylene, coronene, fluoranthene, phenanthrene, anthracene, anthanthrene, and benzo(g,h,i)perylene. The primary constituents of total POM emissions are fluoranthene (42 percent), pyrene (18 percent), benzo(a)pyrene (11 percent), phenanthrene (11 percent), and benzo(e)-pyrene (9 percent).

[e] Specific compounds identified were benzo(a)pyrene, pyrene, benzo(e)pyrene, and fluoranthene. Fluoranthene and pyrene accounted for 87 percent of total POM emissions.

[f] Factor represents both particulate and gaseous POM emissions. Fifty-six specific POM compounds were analyzed for during these tests. Specific compounds identified were naphthalene, phenanthrene, fluoranthene, pyrene, chrysene, benzo(a)-pyrene, o-phenylene pyrene, and benzo(g,h,i)perylene. The primary constituents of total POM emissions were phenanthrene (31 percent), pyrene (30 percent), chrysene (16 percent), and naphthalene (11 percent). Factor represents the average of three tests.

[g] Factor represents both particulate and gaseous POM emissions. Twenty-one specific POM compounds were analyzed for during these tests. Generally, the majority of POM was measured in a gaseous as opposed to particulate phase.

[h] This factor is the average of single emission tests on three boilers. The range of emissions was 1.28 to 31.3 lb/10^{12} Btu. For the three tests, total POM factors ranged from 0.55 to 13.5 pg/J (1.28 to 31.3 lb/10^{12} Btu). The primary constituents of total POM emissions were phenanthrene (64 percent), fluoranthene (17 percent), and pyrene (6 percent).

[i] This factor is the average of single emission tests on three boilers. The range of emissions was 1.21 to 43.4 lb/10^{12} Btu. For the three tests, total POM factors ranged from 0.52 to 18.7 pg/J (1.21 to 43.4 lb/10^{12} Btu). The primary constituents of total POM emissions were phenanthrene (51 percent), methylanthracenes/phenanthrenes (23 percent), and fluoranthene (11 percent).

[j] This factor is the average of single emission tests on five boilers. The range of emissions was 1.3 to 210 lb/10^{12} Btu. For the five tests, total POM factors ranged from 0.56 to 90.3 pg/J (1.3 to 210 lb/10^{12} Btu). The primary constituents of total POM emissions were phenanthrene (32 percent), anthracene (30 percent), and fluoranthene (30 percent).

TABLE C-87. MEASURED UNCONTROLLED TOTAL POM EMISSION FACTORS FOR RESIDENTIAL AND SMALL COMMERCIAL BOILERS

Boiler Type	Coal Type	Total POM Emission Factor lb/10^{12} Btu-heat Input	Reference
Underfeed Stoker	[a]	13.8[b,c]	Hangebrauck *et al.*, 1964
Cast Iron Underfeed Stoker	[a]	210[b,d]	Hangebrauck *et al.*, 1964
Hand Stoked Hot Air Furnace	[a]	8,780[b,e]	Hangebrauck *et al.*, 1964
Underfeed Stoker	[a]	3,285[b,f]	Hangebrauck *et al.*, 1967
Underfeed Stoker	[a]	2,076[b,g]	Hangebrauck *et al.*, 1967
Underfeed Stoker Hot Air Furnace	[a]	1,881[b,h]	Hangebrauck *et al.*, 1967
Underfeed Stoker Hot Air Furnace	[a]	432[b,i]	Hangebrauck *et al.*, 1967
Hand Stoked Hot Air Furnace	[a]	32,800[b,j]	Hangebrauck *et al.*, 1967
Hand Stoked Hot Air Furnace	[a]	84,561[b,k]	Hangebrauck *et al.*, 1967
Underfeed Stoker	Bituminous	3,480[l]	Suprenant *et al.*, 1980b
Underfeed Stoker	Bituminous	395[l]	Suprenant *et al.*, 1980b
Underfeed Stoker	High-Volatile Bituminous	13,400[l,m]	Giammar *et al.*, 1976
Underfeed Stoker	High-Volatile Bituminous	12,800[l,m]	Giammar *et al.*, 1976
Underfeed Stoker	High-Volatile Bituminous	3,600[l,m]	Giammar *et al.*, 1976
Underfeed Stoker	High-Volatile Bituminous	1,920[l,m]	Giammar *et al.*, 1976
Underfeed Stoker	High-Volatile Bituminous	1,380[l,m]	Giammar *et al.*, 1976
Underfeed Stoker	High-Volatile Bituminous	844[l,m]	Giammar *et al.*, 1976
Underfeed Stoker	Subbituminous	1,970[l,m]	Giammar *et al.*, 1976
Underfeed Stoker	Subbituminous	2,150[l,m]	Giammar *et al.*, 1976
Underfeed Stoker	Subbituminous	658[l,m]	Giammar *et al.*, 1976
Underfeed Stoker	Subbituminous	1,610[l,m]	Giammar *et al.*, 1976
Underfeed Stoker	Subbituminous	1,410[l,m]	Giammar *et al.*, 1976
Underfeed Stoker	Low-Volatile Bituminous	4,050[l,n]	Giammar *et al.*, 1976
Underfeed Stoker	Processed Lignite Char	374[l,o]	Giammar *et al.*, 1976
Underfeed Stoker	Anthracite	159[l,o]	Giammar *et al.*, 1976
Underfeed Stoker	Anthracite	22.2[l,o]	Giammar *et al.*, 1976
Underfeed Stoker	Bituminous	18,000[p]	DeAngelis and Reznik, 1979
Underfeed Stoker	Bituminous	2,000[p]	DeAngelis and Reznik, 1979

TABLE C-87. MEASURED UNCONTROLLED TOTAL POM EMISSION FACTORS FOR RESIDENTIAL AND SMALL COMMERCIAL BOILERS (Continued)

Boiler Type	Coal Type	Total POM Emission Factor lb/10^{12} Btu-heat Input	Reference
Magazine Feed	Anthracite	49.4^{q,r}	Giammar *et al.*, 1976
Magazine Feed	Anthracite	9.7^{q,s}	Giammar *et al.*, 1976
Hand Stoked	Anthracite	57.5^{q,t}	Giammar *et al.*, 1976
Magazine Feed	Bituminous	8,177^{q,u}	Giammar *et al.*, 1976
Magazine Feed	Bituminous	2,632^{q,v}	Giammar *et al.*, 1976
Hand Stoked	Bituminous	4,274^{q,w}	Giammar *et al.*, 1976

[a] Data not reported in the available literature.

[b] Factors represent primarily particulate POM emissions. Ten specific POM compounds were analyzed for during these tests.

[c] Specific compounds identified were benzo(a)pyrene, pyrene, benzo(e)pyrene, phenanthrene, and fluoranthene. The primary constituents of total POM emissions were fluoranthene (51 percent), pyrene (27 percent), and phenanthrene (16 percent).

[d] Specific compounds identified were benzo(a)pyrene, pyrene, benzo(e)pyrene, benzo(g,h,i)perylene, coronene, phenanthrene, and fluoranthene. The primary constituents of total POM emissions were fluoranthene (50 percent), phenanthrene (31 percent), and pyrene (8 percent).

[e] Specific compounds identified were benzo(a)pyrene, pyrene, benzo(e)pyrene, benzo(g,h,i)perylene, coronene, perylene, anthanthrene, anthracene, phenanthrene, and fluoranthene. The primary constituents of total POM emisisons were phenanthrene (25 percent), fluoranthene (25 percent), pyrene (15 pencent), anthracene (10 percent), and benzo(a)pyrene (10 percent).

[f] All ten POM compounds listed in footnote e were also identified in these emissions. The primary constituents of total POM emissions were phenanthrene (41 percent), fluoranthene (22 percent), pyrene (20 percent), and anthracene (5 percent).

[g] All ten POM compounds listed in footnote e except coronene were also identified in these emissions. The primary constituents of total POM emissions were phenanthrene (37 percent), pyrene (20 percent), fluoranthene (16 percent), and benzo(a)pyrene (9 percent).

[h] All ten POM compounds listed in footnote e were also identified in these emissions. The primary constituents of total POM emissions were fluoranthene (37 percent), phenanthrene (20 percent), pyrene (19 percent), and benzo(a)pyrene (8 percent).

[i] All ten POM compounds listed in footnote e except coronene and anthanthrene were also identified in these emissions. The primary constituents of total POM emissions were fluoranthene (39 percent), phenanthrene (26 percent), and pyrene (23 percent).

[j] All ten POM compounds listed in footnote e were also identified in these emissions. The primary constituents of total POM emissions were fluoranthene (29 percent), pyrene (18 percent), phenanthrene (15 percent), benzo(a)pyrene (11 percent), and benzo(g,h,i)perylene (9 percent).

[k] All ten POM compounds listed in footnote e were also identified in these emissions. The primary constituents of total POM emissions were fluoranthene (29 percent), pyrene (24 percent), phenanthrene (20 percent), and benzo(a)pyrene (9 percent).

[l] Factor represents both particulate and gaseous POM emissions. Twenty-two specific POM compounds were analyzed for during these tests. The compounds analyzed for included anthracene, phenanthrene, methyl anthracenes, fluoranthene, benzo(c)phenanthrene, chrysene, benz(a)anthracene, methyl chrysenes, 7,12-dimethylbenz(a)anthracene, benzofluoranthenes, benzo(a)pyrene, benzo(e)pyrene, perylene, 3-methylcholanthrene, indeno(1,2,3-c,d)pyrene, benzo(g,h,i)perylene, dibenzo(a,h)anthracene, dibenzo(c,g)carbazole, dibenzo(a,i)pyrene, and dibenzo(a,h)pyrene.

TABLE C-87. MEASURED UNCONTROLLED TOTAL POM EMISSION FACTORS FOR RESIDENTIAL AND SMALL COMMERCIAL BOILERS (Continued)

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[m]The predominant POM compounds occurring during high-volatile bituminous coal combustion were anthracene, phenanthrene, methyl anthracenes, fluoranthene, pyrene, and methyl pyrene/fluoranthene.

[n]The predominant POM compounds occurring during low-volatile bituminous coal combustion were anthracene, phenanthrene, methyl anthracenes, fluoranthene, chrysene/benz(a)anthracene, methyl chrysenes, pyrene, and methyl pyrene/fluoranthene.

[o]The predominant POM compounds occurring during processed lignite char and anthracite coal combustion were anthracene, phenanthrene, methyl anthracenes, fluoranthene, pyrene, chrysene/benz(a)anthracene, and benzofluoranthenes.

[p]Factor represents both particulate and gaseous POM emissions. Individual POM compounds measured were not identified.

[q]Factor represents both particulate and gaseous POM emissions. Eighteen specific POM compounds were analyzed for during these tests.

[r]The primary constituents of total POM emissions were phenanthrene (23 percent), fluoranthene (18 percent), pyrene (13 percent), chrysene (12 percent), benzo(a)anthracene (11 percent), and naphthalene (11 percent). The test was conducted under high burn rate conditions.

[s]The primary constituents of total POM emissions were fluoranthene (26 percent), phenanthrene (25 percent), pyrene (15 percent), chrysene (6 percent), acenaphthene (4 percent), acenaphthylene (4 percent), benzo(a)anthracene (4 percent), and benzo(k)fluoranthene (4 percent). The test was conducted under low burn rate conditions.

[t]The primary constituents of total POM emissions were naphthalene (31 percent), phenanthrene (20 percent), acenaphthylene (14 percent), fluoranthene (10 percent), pyrene (8 percent), and chrysene (3 percent). The test was conducted under moderate burn rate conditions.

[u]The primary constituents of total POM emissions were acenaphthylene (24 percent), naphthalene (18 percent), phenanthrene (17 percent), fluoranthene (8 percent), anthracene (5 percent), pyrene (5 percent), fluorene (5 percent), and benzo(k)fluoranthene (4 percent). The test was conducted under high burn rate conditions.

[v]The primary constituents of total POM emissions were naphthalene (19 percent), phenanthrene (16 percent), anthracene (9 percent), benzo(k)fluoranthene (8 percent), fluorene (8 percent), fluoranthene (7 percent), pyrene (6 percent), benzo(a)pyrene (5 percent), and benzo(a)anthracene (4 percent). The test was conducted under low burn rate conditions.

[w]The primary constituents of total POM emissions were naphthalene (11 percent), acenaphthylene (11 percent), phenanthrene (11 percent), benzo(k)fluoranthene (9 percent), fluoranthene (9 percent), fluorene (7 percent), pyrene (6 percent), benzo(a)anthracene (6 percent), anthracene (5 percent), indeno(1,2,3-c,d)perylene (5 percent), and chrysene (5 percent). The test was conducted under moderate burn rate conditions.